

3D Printing Technologies

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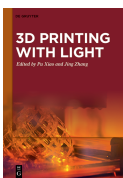


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3D Printing Technologies

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Ajay Kumar, Parveen Kumar, Naveen Sharma
and Ashish Kumar Srivastava

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Finally, the editors obligate this work to the divine creator and express their indebtedness to the "ALMIGHTY" for gifting them power to yield their ideas and concepts into substantial manifestation. The editors believe that this book would enlighten the readers about each feature and characteristics of 3D printing.

Dr. Ajay Kumar
Mr. Parveen Kumar
Dr. Naveen Sharma
Dr. Ashish Kumar Srivastava

Preface

Conventional manufacturing is typically based on removing or reshaping the bulk material, whereas nature generates the desired shape by additive mechanisms. 3D printing is a method of manufacturing parts and products directly from design data, by adding layers of materials to obtain the final shape and size with high accuracy and negligible waste, without any expensive dedicated tooling. It enables radical product redesign and can create complex shapes not possible otherwise with new material properties.

3D printing is emerging as a solution for manufacturing complex geometries for a large variety of applications, including biological objects like human tissues or body parts. This technology is having a disruptive impact on design methods and manufacturing processes. 3D printing has the potential to revolutionize manufacturing capabilities and businesses by utilizing latest developments in artificial intelligence (AI) and Industry 4.0. 3D printing will also transform how and where manufacturing is done across a wide range of industrial sectors and global markets. It will enable us to do things with devices that have never been done before without the use of special machines for early adopters, such as aerospace, automotive, life science, and defense, which will have the biggest impact.

The book covers latest developments like hybrid 3D printing techniques to process different materials that are difficult to process by conventional 3D printing techniques; bioinspired 3D printing and its applications; 3D printing process optimization by various bioinspired algorithms to enhance the characteristics and efficiency, and develop a product in minimum time; integration of 3D printing with AI from prefabrication stage to the final product, with real-time defect detection, control, and process efficiency improvement. The coverage of this book with inputs from worldwide R&D scholars and academics has made revolutionary and unique compendium in the field of 3D printing. All of the above is currently not available at one place. The dearth of a logical platform with all knowledge about 3D printing has motivated the authors to undertake the responsibility of collating the technological developments and advancements in 3D printing from experts in their domains and dissipating them in the form of a book.

The book consists of 17 chapters that describe perspectives of 3D printing technologies, digital manufacturing, AI, and Industry 4.0. Chapter 1 presents the potential use of 3D printing technology in antenna construction to reduce the cost and weight of antennas. Also, this chapter tries to briefly demonstrate how to make an antenna using 3D printing. Chapter 2 discusses a bibliometric and thematic analysis of three-dimensional (3D) bioprinting technology from 2012 to March 2023, with a focus on biomaterials and tissue engineering. Chapter 3 presents a detailed review on additive manufacturing (AM)-based fabrication of compositionally complex alloys from the viewpoints of structure–property correlation and alloy fabrication techniques. Chapter 4 provides a detailed re-

view of insights into the design for additive manufacturing (DfAM) concepts in AM, and the most up-to-date applications of machine learning concepts in integrating DfAM are reviewed. Chapter 5 summarizes various AM techniques for bioprinting along with their advantages, limitations, and case studies. Chapter 6 investigates the feasibility of a 3D printer producing sterile polyether-ether-ketone implants. Two printer configurations are analyzed using computational fluid dynamics to eliminate velocity fluctuations while optimizing heat transfer. Simulation shows the achievability of laminar flow ensuring a sterile print environment. Chapter 7 aims to conduct a comprehensive review of 4D printing technology and its integration with Industry 4.0 in the context of Indian manufacturing. The chapter also discusses the benefits and challenges of implementing 4D printing in the manufacturing sector in India, highlighting the critical role of materials science and engineering in enabling this technology. Chapter 8 aims to provide a detailed review of smart material structures and an overview of the concepts and advancements in 4D printing, and explore various manufacturing methods that have been developed to achieve 4D printing capabilities and recent developments in the field. Chapter 9 looks into the process parameters involved in the direct metal laser sintering process, their impact on product quality, and post processes in order to enhance properties. Chapter 10 focuses on composite material drilling-related delamination. Spindle speed, feed, and interactions are studied for their impact on drilling's cutting characteristics. Chapter 11 utilizes *k*-means clustering, an unsupervised machine learning algorithm from the Scikit-learn machine learning library of Python, to identify clusters in an experimental dataset that predicts the dimensional accuracy of printed PDMS-CNT ink. Chapter 12 provides a comprehensive review of the latest developments in 3D printing and its applications focusing on its applications in the biomedical industry, construction, education, fashion industry, and food industry. Chapter 13 provides a thorough examination of 3D printing procedures, including conventional and unconventional approaches. Chapter 14 discusses advantages, characteristics, and applications of AM and 4D printing in biomedical sectors. Chapter 15 discusses the potential of 3D printing in medical, agriculture, engineering, and other sectors. Chapter 16 provides a comprehensive review of the latest developments in 3D printing and its applications in biomedical industry, construction, and space exploration. The analysis is done using the existing research and case studies and shows the remarkable potential of 3D printing to revolutionize these industries. Chapter 17 examines the subject of design optimization in the context of 3D printing, with a specific emphasis on the investigation of design strategies and the application of optimization techniques to enhance material utilization.

This book is intended for both the academia and the industry. The postgraduate students, Ph.D. students, and researchers in universities and institutions who are involved in the areas of 3D printing will find this compilation useful.

The editors acknowledge the professional support received from De Gruyter and express their gratitude for this opportunity.

Reader's observations, suggestions, and queries are welcome.

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1 3D-printed antennas

Abstract: In this chapter, 3D-printed microwave antenna is surveyed. Various types of 3D printing techniques applied to microwave antennas are briefly reviewed. Prototypes of circular horn antennas are designed as examples of this survey. The designed circular horns are printed using acrylonitrile butadiene styrene, with the surface painted with a conducting paint. The design steps and the printing process of the printed circular horn are described in detail. Several parameters of the printed horn antenna, such as return loss, radiation pattern, gain, and polarization, were analyzed and evaluated based on the measurement results. Also, the measured results with the electromagnetic simulation results were compared for verification.

Keywords: 3D printer, circular horn antenna, acrylonitrile butadiene styrene, conducting paint, fused deposition modeling, microwave

1.1 Introduction

3D printing is an alternative manufacturing technology that creates 3D objects, layer by layer. The application of 3D-printed technology to microwave antennas has demonstrated that their mass can be reduced by up to 50%, production time can be reduced by more than 40%, and manufacturing costs can be reduced by more than 60%. Besides, 3D printing is able to print/fabricate antennas with complex shapes, which are difficult to handle with conventional machining techniques [1, 2]. The mechanism of 3D printing includes melting, sintering, deposition, solidification, etc. The 3D printing materials can be metal alloys, polymers, or ceramics [3, 4].

Fig. 1.1 shows the number of publications indexed in the Scopus [5] and Web of Science (WoS) [6] platforms from 2012 to 2022 using the search keyword, “3D Print and Antenna.” Obviously, the number of studies related to antennas using 3D-printed

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technology is increasing [7–32]. Most of the documents are published by IEEE, Wiley, Elsevier, MDPI, IET letters, Springer Nature, and other publishers, as shown in Fig. 1.2.

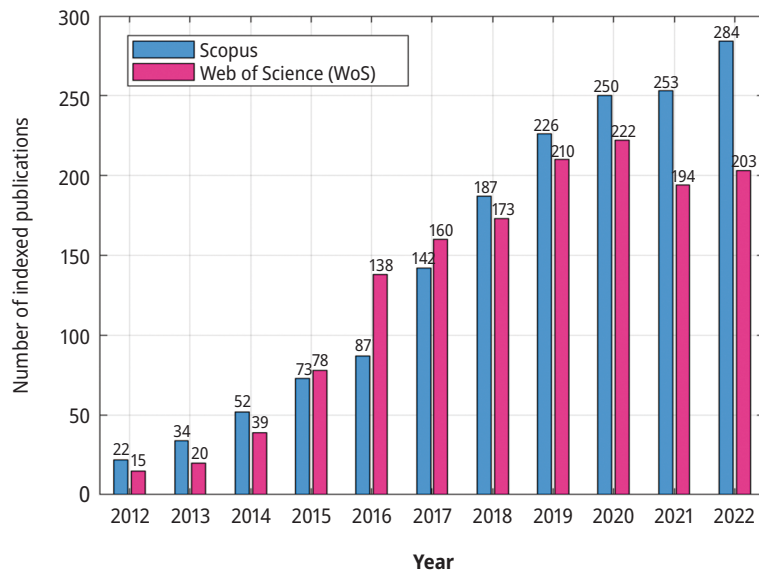


Fig. 1.1: Indexed documents in Scopus and WoS platforms, based on “3D Print and Antenna” as a keyword.

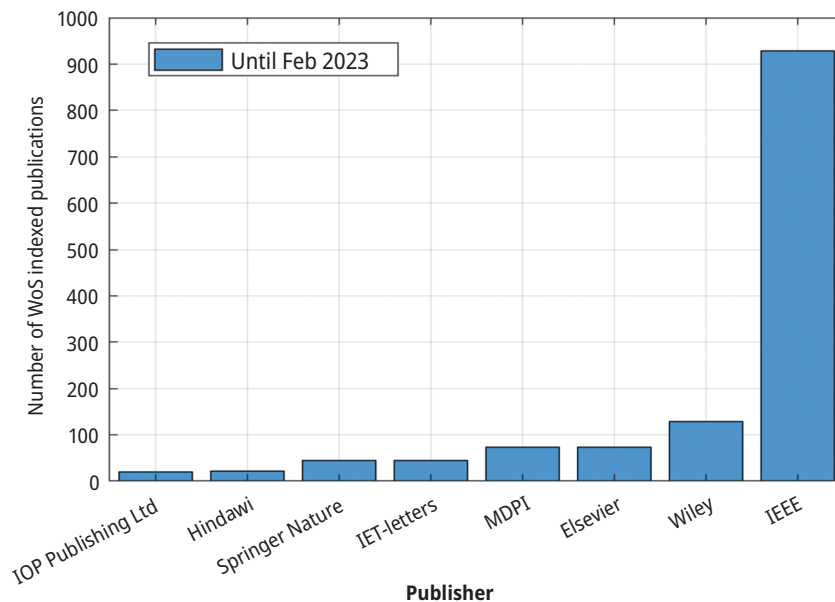


Fig. 1.2: Total indexed documents in the WoS platform based on “3D Print and Antenna” keyword, contributed by various publishers.

In this chapter, various 3D printing techniques applied to antenna fabrication are briefly introduced and reviewed. In addition, a simple circular horn example is used to demonstrate how 3D printing can be used for antenna manufacturing. Up to four different dimensions/sizes of X-band circular horn antennas are printed and tested. The steps of design, simulation, sketch, 3D printing, and measurement of the 3D-printed circular horns are described in detail. This chapter is also intended to be a teaching/tutorial material for engineering design, such as problem-based learning projects for undergraduate or graduate students. The 3D-printed circular horn antenna design and fabrication process can be used for other antenna designs.

1.2 3D printing techniques and materials

At present, the 3D printing technology used for microwave antenna manufacturing can be divided into 4 categories, namely **(1)** fused deposition modeling (FDM) [9, 14, 15, 17–19, 21, 26, 28–30], **(2)** stereolithography (SLA) [11, 12, 16, 21, 31], **(3)** Inkjet/PolyJet [7, 10, 18, 20, 22,–24], and **(4)** selective laser sintering (SLS)/selective laser melting (SLM) [8, 13, 25, 27, 32]. The printing materials of each 3D printing technology are different [33–38]. For example, FDM's printing materials are solid polymer-based materials in the form of filaments. On the other hand, the printing material used in SLA is liquid photosensitive resin. InkJet/PolyJet can print dielectric and conductive nanoparticles in liquid form and for SLS/SLM, the printing material should only be in powder form.

Besides, the various mechanisms of the 3D printing technology are illustrated in Fig. 1.3. Each technology has its advantages and trade-offs. The technologies that are used to print different kinds of antennas are listed in Tab. 1.1. Normally, the antenna is a metal device (except the dielectric lens or dielectric resonator antennas) to guide the propagated signal; hence, the antenna printed with a dielectric material needs to be metallized on the surface of the dielectric with conductive paint/ink or copper tape [39–41]. In addition, some printed antenna surfaces are first sprayed with a thin layer of copper paint to provide a conductive surface and then recoated with nickel as a second conductive layer using the electrodeposition coating technique. Despite this, the total thickness, t of the conductive layer on the dielectric material surface should be greater than the skin depth of the conductive paint, namely:

$$t \gg \frac{1}{(\pi f \mu_o \sigma)^{1/2}} \quad (1.1)$$

where f and μ_o are the operating frequency (in unit Hz) and permeability of free space ($4\pi \times 10^{-7}$ H/m), respectively. On the other hand, σ is the conductivity value (in unit S/m) of the conductive paint/ink.

For dielectric lens or dielectric resonator antenna that is fabricated using 3D printing technology, the dielectric constant, ϵ_r , and the loss tangent, $\tan \delta$ of the printed material will play important parameters [42–44]. The typical values of ϵ_r and $\tan \delta$ of some commercial 3D printing materials are listed in Tab. 1.2. for reference. Several printing materials and their typical dielectric properties (ϵ_r and $\tan \delta$) are plotted in Fig. 1.4 [34]. Obviously, polymer-based materials usually have dielectric constant, ϵ_r , values between 2 and 10. Most ceramic-based materials have higher values of dielectric constant ($\epsilon_r > 10$) but have a low loss tangent ($\tan \delta < 10^{-3}$). Indeed, the value of ϵ_r and $\tan \delta$ for the same material will slightly vary with different brands or material manufacturers. In addition, the value of ϵ_r and $\tan \delta$ are operating frequency- and temperature-dependent parameters. Normally, the ϵ_r value for most dielectric materials will decrease when the operating frequency, f , increases.

1.2.1 Fused deposition modeling (FDM)

Of the four types, fused deposition modelling (FDM) is most commonly used; it is the easiest and the most economical 3D printing technology. In FDM technology, the printing process used is to extrude a melt filament material through a heated nozzle and deposit it in layers to create the desired object as shown in Fig. 1.3(a). Thus, this technology is also called as fused filament fabrication. FDM is capable of printing a variety of filament polymers such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), thermoplastic polyurethane (TPU), polyethylene terephthalate glycol (PETG), polyamide/Nylon (PA), polyvinyl alcohol (PVA), polycarbonate (PC), high impact polystyrene, polymer wood, and carbon fiber (conductive ABS). The disadvantage of FDM is poor surface roughness, with a typical resolution layer of 0.2 mm. However, the surface roughness can be improved by mechanical post-processing (grinding) or chemical treatment (solvent). FDM 3D printers are the most cost-effective printers.

1.2.2 Stereolithography (SLA)/digital light processing (DLP)

Typically, SLA technology uses a laser or ultraviolet (UV) beam to cure a liquid resin (photopolymer) into the desired solid object as shown in Fig. 1.3(b). Compared with FDM, SLA can produce accurate prototype prints (even irregular shapes) and a good smooth printing surface, with a resolution layer of less than 0.15 mm. On the other hand, digital light processing (DLP) uses light-emitting diode projection to replace laser systems as the UV source, which reduces printing time as shown in Fig. 1.3(c).

1.2.3 InkJet / polyjet

3D inkjet is a printing process that involves depositing liquid (or semisolid) materials such as polymers, dielectric nanoparticles, and conductive nanoparticles. PolyJet is a type of inkjet, and its printing material must be a liquid photopolymer. PolyJet, also known as aerosol jet printing, builds by jetting liquid photopolymer layer by layer while curing it with UV light as shown in Fig. 1.3(d). PolyJet can achieve print layer thicknesses as small as μm . The main benefits are smooth surface finish and high resolution of the printed parts. Polyjet printers can have multiple print nozzles (print heads), which enables the printer to print multicolor and multi-material parts.

1.2.4 Selective laser sintering (SLS)/selective laser melting (SLM)

SLS technology also uses laser beam fusion. However, the material used is a powder material. SLS technology uses a laser beam to fuse powder particles (nylon powder such as PA11 and PA12), transforming the powder into a solid as illustrated in Fig. 1.3(e). For metal 3D printing, the SLM uses more laser power (> 200 Watts) than SLS (~ 30 Watts), and allows metal alloy powders as construction materials, such as aluminum (AlSi10Mg), titanium (Ti6Al4V), stainless steel, or Invar. SLM is also sometimes referred to as direct metal laser sintering or powder bed fusion (PBF). In addition, SLM 3D printers are the most expensive, compared to other types of 3D printers.

1.3 Methodology

1.3.1 Circular horn antenna design formulas

In this chapter, X-band circular horn antennas are designed, and their general structure and dimensions are shown in Fig. 1.5. The optimal gain, G (dimensionless), expressed in terms of axial length, L (in unit meters) is given as [45]

$$G \approx 15.9749 \left(\frac{L \times f}{c} \right) + 1.7209 \quad (1.2)$$

Rearranging (1.2) yields

$$L \approx \left(\frac{c}{f} \right) [0.062598201 \times G - 0.10772524] \quad (1.3)$$

where c and f are the speed of light in free space (in ms^{-1}) and operating frequency (in Hz), respectively. On the other hand, the relationship between optimal gain, G (dimensionless), and diameter, D (in meters) of the circular horn aperture is written as [45]

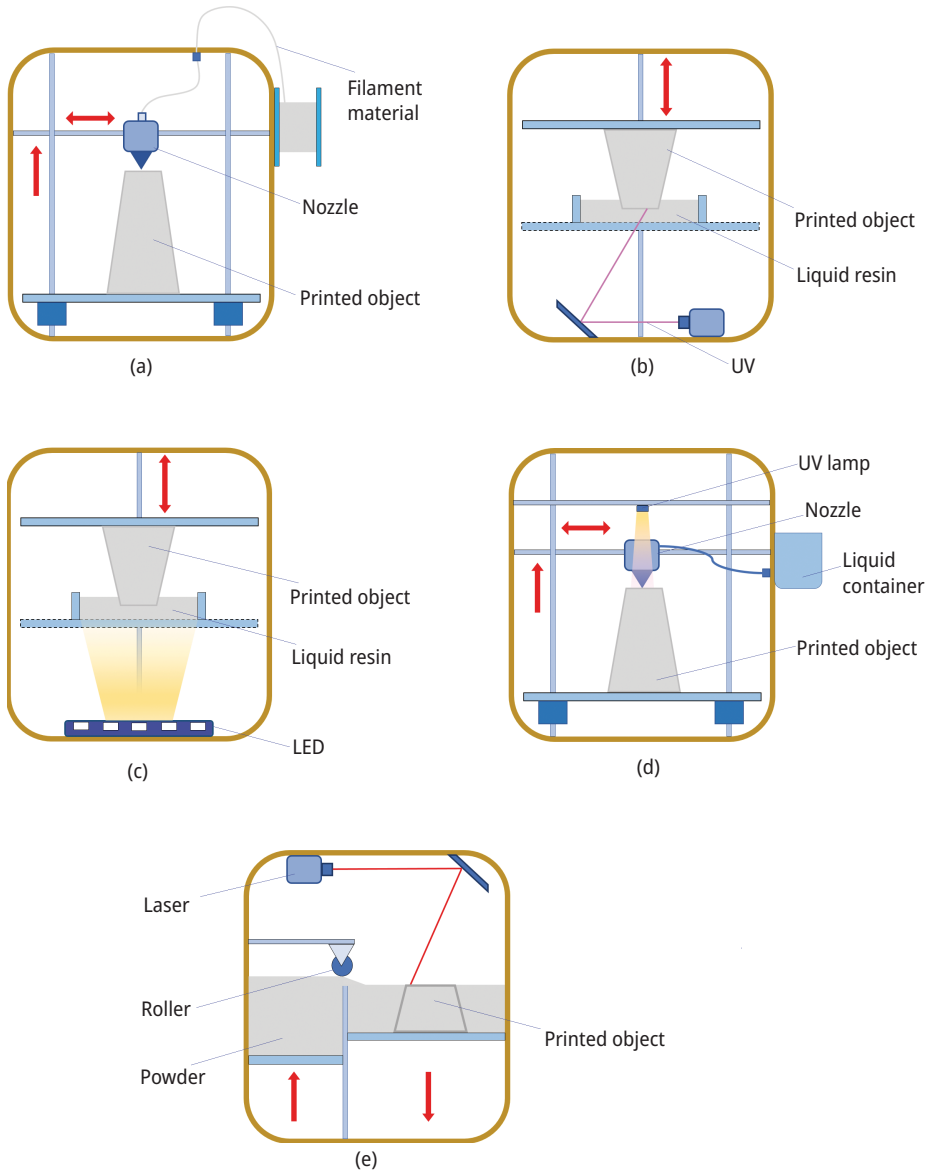


Fig. 1.3: (a) Fused deposition modeling (FDM), (b) stereolithography (SLA), (c) digital light processing (DLP), (d) Inkjet, and (e) selective laser sintering (SLS).

Tab. 1.1: Application, materials, and specifications of 3D printing in antenna fabricating.

Antenna	3D printing technology	Printing material	Printing resolution/roughness (μm)	Reference
Yagi-Uda antenna	Inkjet	Cabot CCI-300 silver nanoparticle-based ink	~5	[7]
		Liquid crystalline polymer (Rogers ULTRALAM 3850)		
		SU-8 polymer-based thick dielectric ink		
Conical horn	SLM	Cu-15Sn	127.42	[8]
Dual-ridged horn	FDM	ABS	200	[9]
Pyramidal horn	Inkjet	420 SS + Cu composite	6.26	[10]
Gap-waveguide array antennas	SLA	–	~250	[11]
Double-ridged TEM horn	SLA	–	–	[12]
Stepped, double-ridged square horn	SLM	Aluminum alloy	6	[13]
		Copper alloy	3	
Coaxial-fed horn integrated dielectric resonator antenna	FDM	PLA	–	[14]
Exponentially tapered pyramidal horn	FDM	ABS	200	[15]
Pyramidal horn	SLA	Liquid photosensitive resin	–	[16]
Tunable circularly polarized microstrip patch antenna	FDM	ABS	–	[17]
Four-element steerable phased-array antenna	Polyjet	VeroWhite resin	16	[18]
	FDM	ABS	100	
Elliptical double-ridged horn	FDM	ABS	100	[19]
Corrugated plate antennas	Polyjet	Vero clear	16	[20]
Feeding horns and holding fixtures	FDM	PLA	250	[21]
Parallel-plate circularly polarized Luneburg lens	SLA	Photopolymer resin FLGPCL02	140	[21]

Tab. 1.1 (continued)

Antenna	3D printing technology	Printing material	Printing resolution/roughness (μm)	Reference
Rigid-flex Vivaldi antenna	Polyjet	Liquid crystal polymer (Rogers 3850HT)	–	[22]
Planar form antenna	Inkjet	AgIC-AN01 Silver Nano Ink	1	[23]
Rectangular patch antennas and transmission lines	Inkjet	AgCite™ nano-silver (conductive ink)	0.3	[24]
		Acrylate (dielectric ink)	2.5	
Axial corrugated horn	DMLS	Aluminum (AlSi10Mg)	100	[25]
Dual-reflector antenna	FDM	PLA	200	[26]
Dual-polarized Vivaldi arrays	SLM	Titanium (Ti6Al4V)	150	[27]
Pyramidal horn	FDM	PLA	300	[28]
Quad-ridged horn antenna	FDM	PLA	–	[29]
Curved patch antenna	FDM	ABS	100	[30]
Antenna lens	SLA	FormLabs high-temperature resin	–	[31]
Wideband corrugated horn	SLM	Aluminum (AlSi10Mg)	20	[32]

Note: SLM, selective laser melting; FDM, fused deposition modeling; SLA, stereolithography; DMLS, direct metal laser sintering.

Tab. 1.2: Commercial 3D printing materials and their dielectric and conductivity properties [33–35, 44].

Printing material	Technology	Dielectric constant, ϵ_r	Loss tangent, $\tan \delta$	Conductivity, σ (S/m)
Acrylonitrile butadiene styrene (ABS)	FDM	~2.69 (1 MHz) ~2.45 (>2 GHz)	~0.012 (1 MHz) ~0.005 (>2 GHz)	–
Polylactic acid (PLA)	FDM	~2.7 (1 MHz) ~2.55 (>2 GHz)	~0.008 (1 MHz) ~0.009 (> 2 GHz)	–
High-impact polystyrene (HIPS)	FDM	~2.49	~ 8.53×10^{-4}	–

Tab. 1.2 (continued)

Printing material	Technology	Dielectric constant, ϵ_r	Loss tangent, $\tan \delta$	Conductivity, σ (S/m)
Polypropylene (PP)	FDM	~2.12 (847 kHz) ~2.03 (typ.)	~ 6.7×10^{-5} (847 kHz) ~ 1.45×10^{-4} (typ.)	–
Cyclic olefin copolymer (COC)	FDM	~2.24	~ 2.17×10^{-4}	–
Polycarbonate (PC)	FDM	~2.67 (847 kHz) ~2.5 (10 GHz)	~0.0118 (847 kHz) ~0.01 (10 GHz)	–
Black Magic 3D (conductive filament)	FDM	–	–	~167
Electrifi (conductive filament)	FDM	–	–	~ 1.67×10^4
Photopolymer resin FLGPCL02	SLA	~2.9	~0.03	–
Liquid photosensitive resin	SLA	~2.54	~0.04	–
FormLabs high temp resin	SLA	~2.66	~0.03	–
Resin (FormLabs Durable)	SLA	~2.78	~0.06	–
Clear acrylic	SLA	~2.6 (10 GHz)	~0.019 (10 GHz)	–
Black acrylic	SLA	~2.6 (10 GHz)	~0.021 (10 GHz)	–
Gray engineering resin	SLA	~2.9 (10 GHz)	~0.032 (10 GHz)	–
High temp acrylic	SLA	~2.6 (10 GHz)	~0.020 (10 GHz)	–
Rogers Corp 2.8 Dk Printable dielectric	SLA/DLP	~2.8 (10 GHz)	~0.0044 (10 GHz)	–
Urethane methacrylate	DLP	~2.9 (10 GHz)	~0.039 (10 GHz)	–
Cyanate ester	DLP	~3.1 (10 GHz)	~0.017 (10 GHz)	–
SU-8 polymer-based thick dielectric ink	Inkjet	~3.2	~0.04	–
Liquid crystalline polymer (Rogers ULTRALAM 3000)	Inkjet	~2.9	~0.0025	–
Liquid crystal polymer (Rogers 3850HT)	Inkjet	~3.14	~0.002	–
Cabot CCI-300 silver nanoparticle-based ink	Inkjet	–	–	~ 1.1×10^7

Tab. 1.2 (continued)

Printing material	Technology	Dielectric constant, ϵ_r	Loss tangent, $\tan \delta$	Conductivity, σ (S/m)
Graphene	Inkjet	–	–	$\sim 4.5 \times 10^4$
VeroWhite resin	Polyjet	~ 2.97 (1.5 GHz) ~ 2.8 (typ.)	~ 0.0285 (1.5 GHz) ~ 0.04 (typ.)	–
Stainless steel 316L	SLM	–	–	$\sim 1.35 \times 10^6$
Aluminum (AlSi10Mg)	SLM	–	–	$\sim 2.3 \times 10^7$
Titanium (Ti6Al4V)	SLM	–	–	$\sim 1.82 \times 10^6$

Note: FDM, fused deposition modeling; SLA, stereolithography; DLP, digital light processing.

$$G \approx 5.1572 \left(\frac{D \times f}{c} \right)^2 - 0.6451 \left(\frac{D \times f}{c} \right) + 1.3645 \quad (1.4)$$

Inserting (1.2) into (1.4), the relationship between axial length, L and diameter, D can be expressed as

$$L \approx 0.32283144182436 \left(\frac{f}{c} \right) D^2 - 0.0403820994184627 \times D - 0.0223099988106342 \left(\frac{c}{f} \right) \quad (1.5)$$

The diameter D of the circular horn aperture is determined by its inverse solution. The `fzero` MATLAB command is applied to (1.5), with known values of L , f , and c , to predict the appropriate value of D . Finally, the axial length l from the circular waveguide junction to horn aperture can be found as

$$l = L \left(1 - \frac{d}{D} \right) \quad (1.6)$$

where d is the diameter (in unit meter) of the circular waveguide that depends on the operating frequency as listed in Tab. 1.3. The efficiency e_A of the aperture horn is given as

$$e_A = \left(\frac{c}{\pi D \times f} \right)^2 \times (10 \log_{10} G) \quad (1.7)$$

However, it is rare to find a commercial adapter that can connect directly to circular waveguides with diameter d . Normally, only coaxial-rectangular adapters of standard size are sold in the market. Therefore, there must be a circular to rectangular wave-

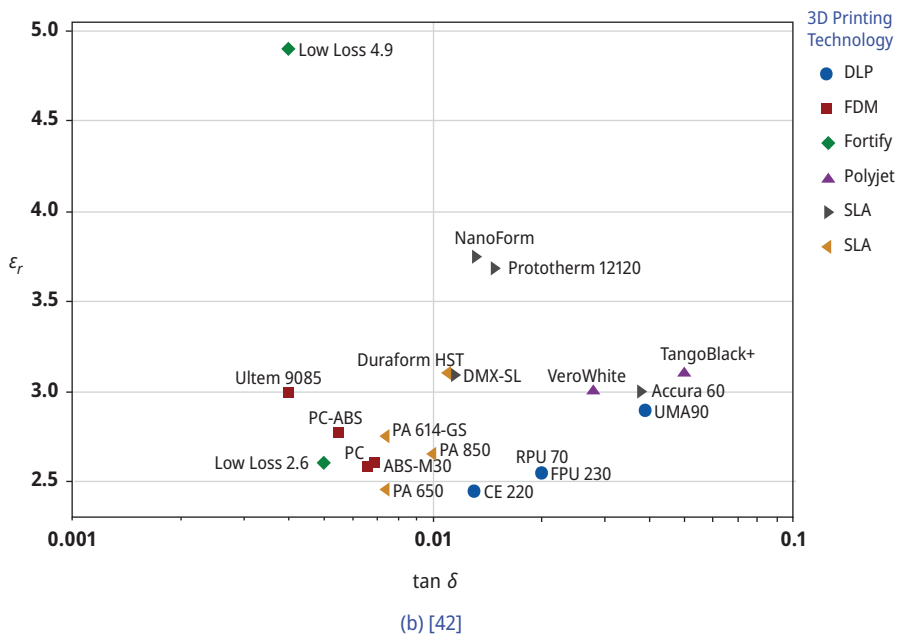
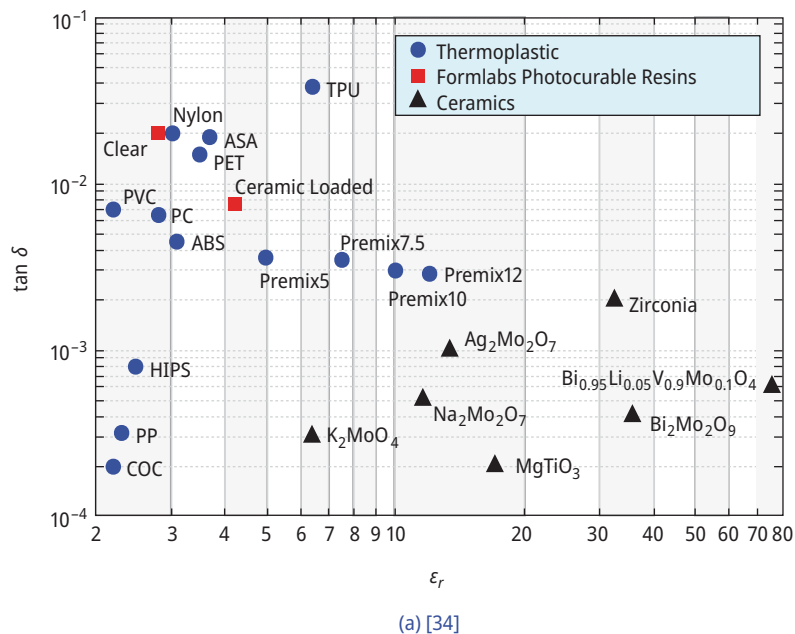


Fig. 1.4: Typical ϵ_r and $\tan \delta$ values of various 3D printing materials [34, 42].

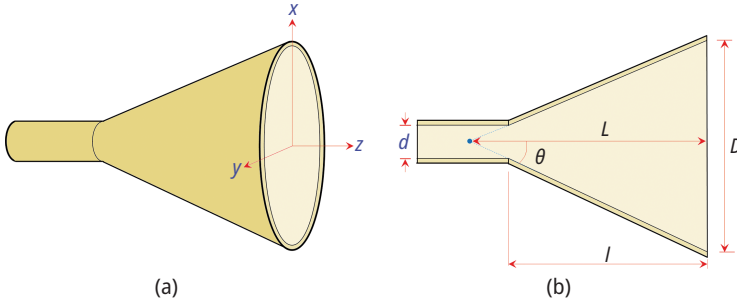


Fig. 1.5: (a) Simple circular horn structure and (b) cross-sectional view of the circular horn.

guide transition between the circular waveguide and the adapter as shown in Fig. 1.6, and the rectangular waveguide at the end of the transition will be connected to the coaxial-rectangular adapter. In this circular horn design, the length of the transition part is fixed to be 10 cm, to provide a good impedance match between the rectangular waveguide (width b and height a) and the circular waveguide (diameter d). Normally, the longer the length of the transition part, the better the impedance match between the rectangular and the circular waveguides.

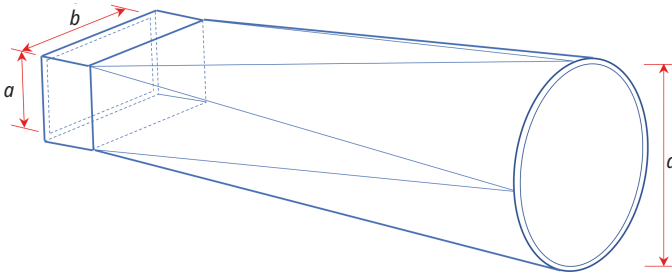


Fig. 1.6: Circular to rectangular waveguide transition part.

As is well known, the diameter d of the circular waveguide is dependent on the operating frequency and its corresponding rectangular waveguide dimensions (width b and height a); refer Tab. 1.3. The flow chart of the circular horn design calculations is illustrated in Fig. 1.7. In this chapter, the user interface (IU) of the circular horn calculator is developed using MATLAB ‘appdesigner’ environment [46] to facilitate the horn design, as shown in Fig. 1.8. The MATLAB codes for the circular horn calculation can be referred to in **Appendix**. Up to three circular horns (namely horns A, B, and C) are designed, based on the desired gain G of 15 dBi, 18 dBi, and 20 dBi at 9 GHz, respectively. The dimensions of the three horns are listed in Tab. 1.4.

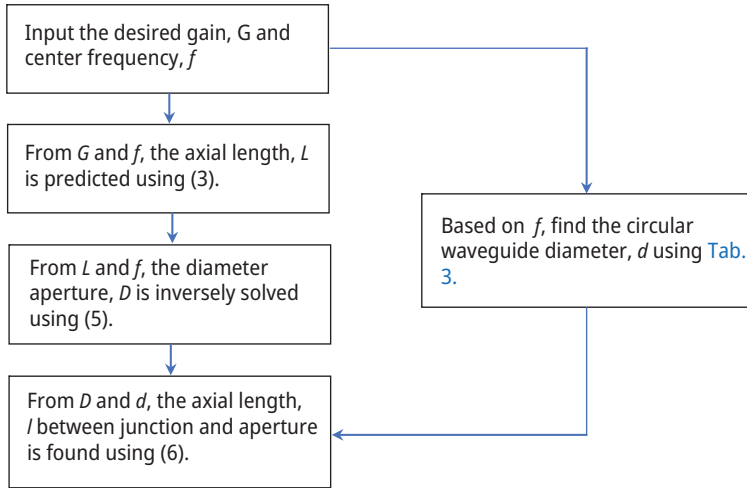


Fig. 1.7: Initial design steps of the circular horn antenna.

Tab. 1.3: Standard diameter d and its operating frequency f .

Diameter d (mm)	Cutoff frequency (GHz)	TE_{11} mode operating frequency (GHz)	Rectangular waveguide aperture dimensions	
			Width b (mm)	Height a (mm)
251.84	0.698	0.803–1.100	247.65	123.82
215.14	0.817	0.939–1.290	195.58	97.79
183.77	0.957	1.100–1.510	165.10	82.55
157	1.12	1.290–1.760	165.10	82.55
134.11	1.311	1.510–2.070	129.54	64.77
114.58	1.534	1.760–2.420	109.22	54.61
97.87	1.796	2.070–2.830	86.36	43.18
83.62	2.102	2.420–3.310	86.36	43.18
71.42	2.461	2.830–3.880	72.14	34.04
61.04	2.88	3.310–4.540	58.17	29.08
51.99	3.381	3.890–5.330	47.549	22.149
44.45	3.955	4.540–6.230	40.386	20.193
38.1	4.614	5.300–7.270	40.386	20.193
32.537	5.402	6.210–8.510	34.849	15.799
27.788	6.326	7.270–9.970	28.499	12.624
23.825	7.377	8.490–11.600	22.86	10.16
20.244	8.685	9.970–13.700	19.05	9.525
17.415	10.057	11.600–15.900	19.05	9.525
15.088	11.649	13.400–18.400	15.799	7.899
12.7	13.842	15.900–21.800	12.954	6.477
11.125	15.794	18.200–24.900	10.668	4.318
9.525	18.446	21.200–29.100	8.636	4.318

Tab. 1.3 (continued)

Diameter d (mm)	Cutoff frequency (GHz)	TE ₁₁ mode operating frequency (GHz)	Rectangular waveguide aperture dimensions	
			Width b (mm)	Height a (mm)
8.331	21.103	24.300–33.200	8.636	4.318
7.137	24.62	28.300–38.800	7.112	3.556
6.35	27.683	31.800–43.000	7.112	3.556
			5.69	2.845
5.563	31.617	36.400–49.800	5.69	2.845
4.775	36.776	42.400–58.100	4.775	2.388
4.369	40.227	46.300–63.500	4.775	2.388
3.581	49.103	56.600–77.500	3.759	1.88
3.175	55.28	63.500–87.200	3.0988	1.5494
2.769	64.462	72.700–99.700	2.54	1.27
2.388	73.552	84.800–116.000	2.54	1.27
2.26	–	90.000–115.000	2.54	1.27
1.91	–	88.000–110.000	2.54	1.27
1.85	–	110.000–140.000	2.032	1.016
1.50	–	140.000–160.000	1.651	0.8255
1.47	–	140.000–180.000	1.651	0.8255
			1.2954	0.6477
1.14	–	180.000–220.000	1.0922	0.5461
1.25	–	170.000–260.000	1.0922	0.5461
0.99	–	220.000–325.000	0.8636	0.4318

Tab. 1.4: Specifications and dimensions of the three 3D-printed circular horns.

Parameters	Circular horn		
	A	B	C
Gain G (dBi)	15	18	20
Center frequency f (GHz)	9.0	9.0	9.0
Circular waveguide diameter d (mm)	27.79	27.79	27.79
Aperture diameter D (mm)	82.80	117.30	147.80
Conical axial length L (mm)	62.35	128.00	204.90
Junction to aperture length l (mm)	41.42	97.67	166.40
Rectangular width b (mm)	22.86	22.86	22.86
Rectangular height a (mm)	10.16	10.16	10.16

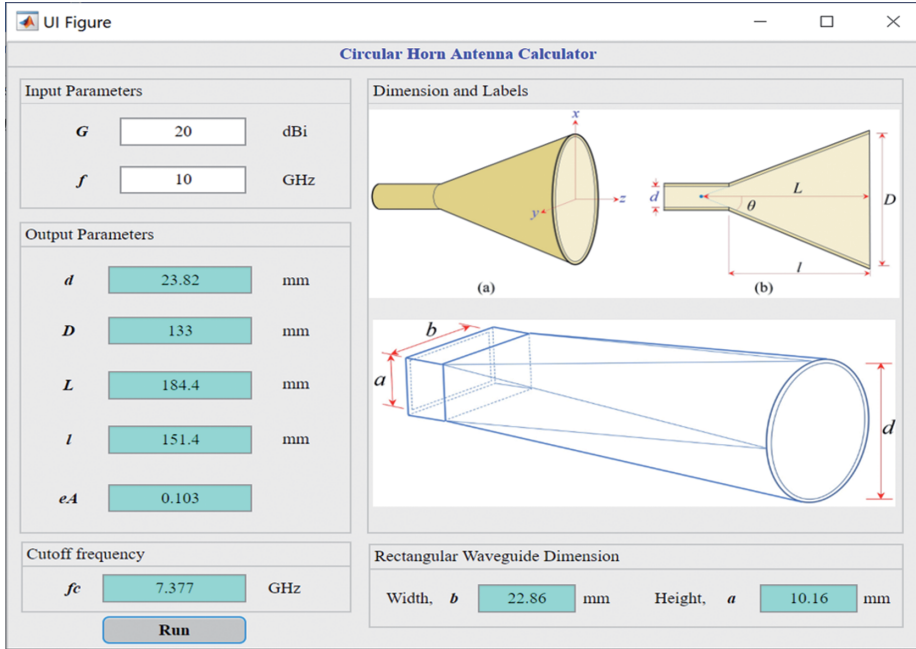


Fig. 1.8: MATLAB-based user interface (IU) of the circular horn antenna calculator.

1.3.2 EM simulation and computer-aided design drawing

The dimensions of the three circular horn antennas (namely A, B, and C) are re-sketched using CST (computer simulation technology) Studio Suite EM simulator [47] as shown in Fig. 1.9(a). For instance, the simulated radiation fields of the horn B are illustrated in Fig. 1.9(b)–(d). It should be noted that the material forming the horn structure in the simulation is a perfectly conductive material. Once the horn is designed and meets the specifications, the CST simulation file of the designed horn is saved (Export) in stereolithography (STL) file format.

Later, the STL file format is opened again using the SolidWorks software [48]. The shape of the horn can be further decorated, and the waveguide flange with screw holes can be added to the horn by using the sketch feature in the software as illustrated in Fig. 1.10.

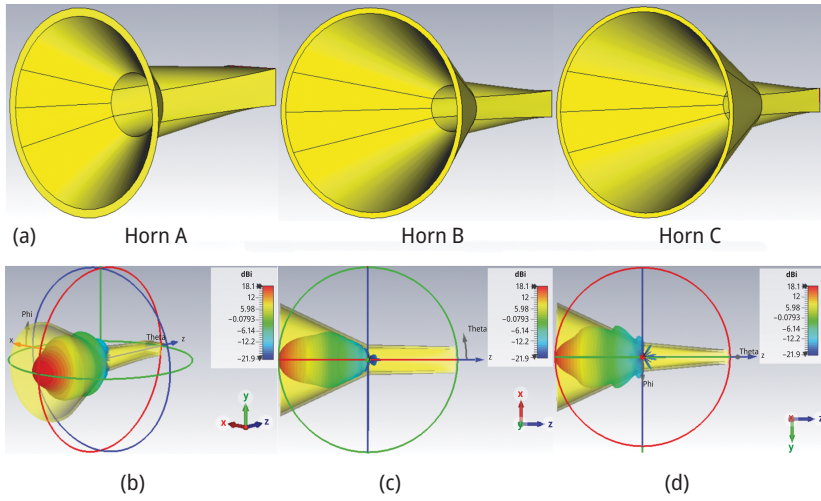


Fig. 1.9: (a) 3D dimension of the circular horns A, B, and C; (b) circular horn B with its 3D radiation pattern; (c) E-plane; and (d) H-plane radiation patterns of horn B at 9 GHz.

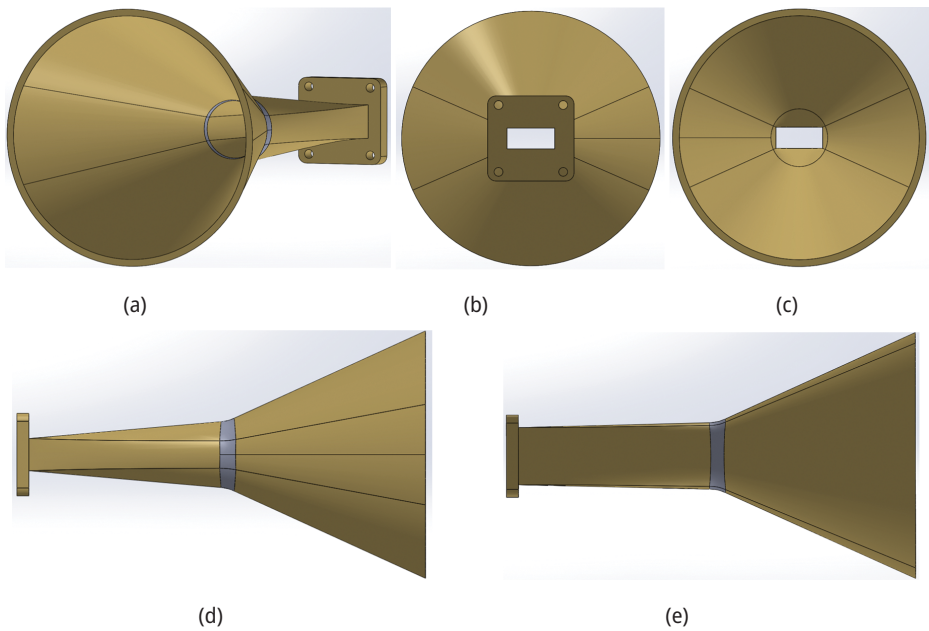
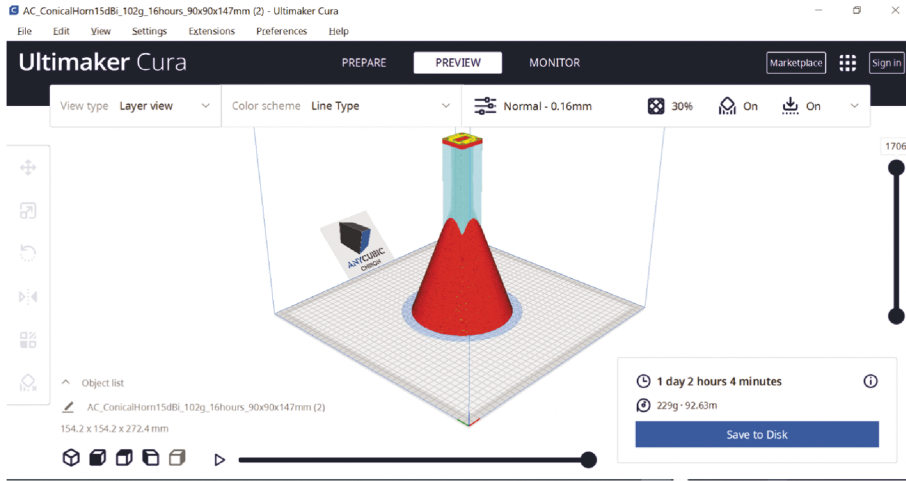


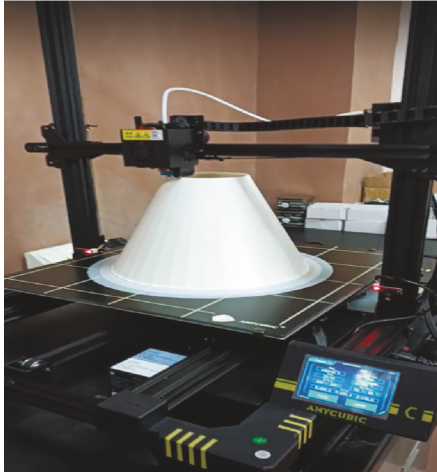
Fig. 1.10: (a) 3D blueprint of the circular horn B; (b) rear; (c) front; (d) side; and (e) top views of the circular horn B.

1.3.3 3D printing process and fabrication

Before starting the 3D printing of the horn, the STL file is opened again with the Ultimaker Cura software to generate the 3D printing G-code in order to convert the 3D horn structure into a series of horizontal layers that could be 3D printed as shown in Fig. 1.11(a). In this fabrication, FDM-based Anycubic Chiron 3D printer, with ABS filament, is used to print the circular horn as illustrated in Fig. 1.11(b) and the raw



(a)



(b)



(c)

Fig. 1.11: (a) 3D printing using G-code generated using Ultimaker Cura software; (b) FDM-based 3D printing; and (c) printed circular horn using ABS filament.

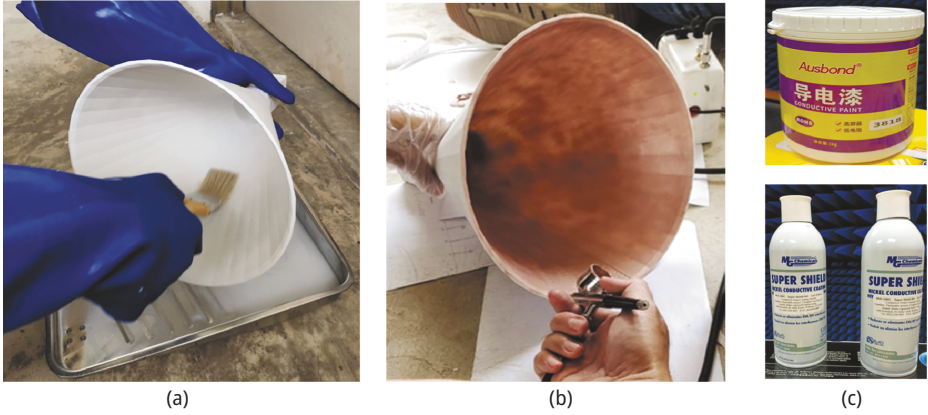


Fig. 1.12: (a) Smooth inner surface of printed horn; (b) spray conductive paint on the inner surface of the horn; and (c) copper and nickel conductive paints.

printed circular horn structure is shown in Fig. 1.11(c). The printing layer height resolution is set to 0.16 mm. It takes about 18 h to a day to complete the 3D print. On the other hand, nearly 102 g, 158 g, and 229 g of ABS filament are used for horn A, B, and C printing, respectively.

Once the horn is completely printed, the inner surface of the horn is made smooth using the XTC-3D solvent [see Fig. 1.12(a)] and allowed to dry at room temperature. After that, the smoothed surface of the horn is sprayed with the conductive paint [see Fig. 1.12 (b)]. In order to ensure the electrical conductivity of the surface, multilayer spray paint is carried out on the surface, namely the bottom layer is coated with a copper conductive paint, and the next layer is coated with a nickel conductive paint [see Fig. 1.12(c)]. After the paint has dried for a day, the resistance, R of the conductive paint surface of the horn is measured with a digital multimeter to ensure that the resistance, R of all surface areas is less than $1\ \Omega$ (to avoid signal leakage from the surface).

1.4 Measurement validation and analysis

1.4.1 Return loss measurements

The return loss $|S_{11}|$ (dB) of the three circular horns are measured using Keysight N9925A FieldFox vector network analyzer (VNA) from 8 to 9 GHz, as illustrated in Fig. 1.13. Before measuring the $|S_{11}|$ of the horn, two calibration procedures are carried out to ensure the high precision and high accuracy of measuring $|S_{11}|$. Initially, the end of the coaxial cable is calibrated using the Keysight 85052D mechanical kit. Afterwards, the coaxial-waveguide adapter is connected to the calibrated end of the

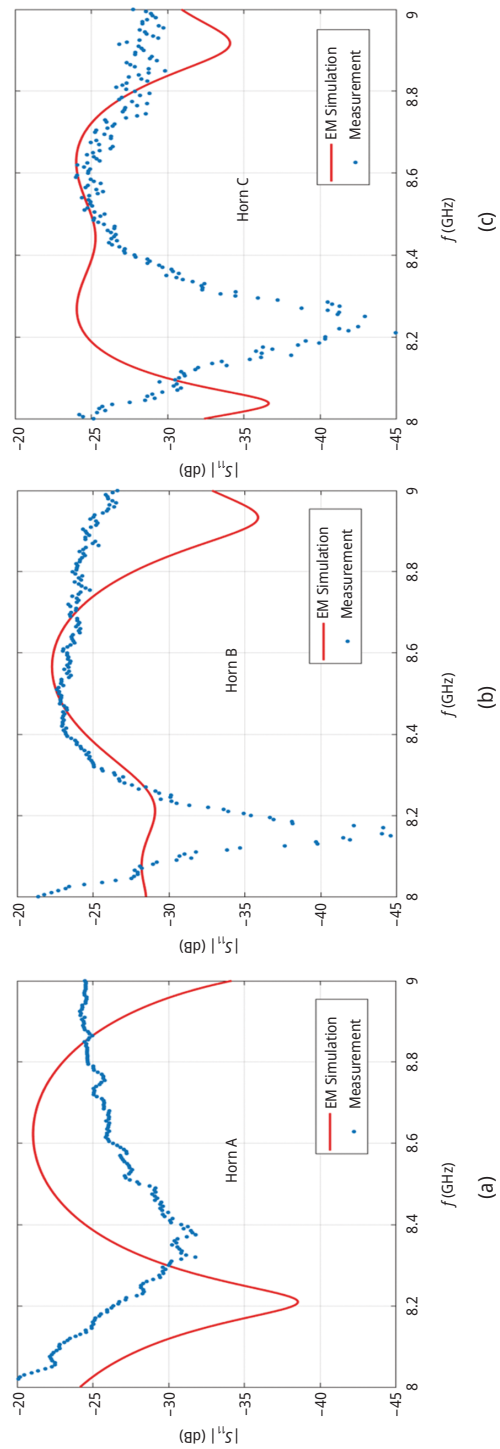


Fig. 1.13: Return loss $|S_{11}|$ versus operating frequency f of circular horns (a) A, (b) B, and (c) C, respectively.

cable and the through-reflect-line (TRL) procedure is used to calibrate the aperture adapter. Finally, the antenna under test is connected to the aperture adapter.

The lower the value of $|S_{11}|$, the better is the impedance matching of the horn antenna to transmit or receive the signal (to lower the transmission power loss due to reflections). The three horns A, B, and C achieved the required matching level; the $|S_{11}|$ values are less than -20 dB (less than 1% power loss); especially horn C has the best impedance match level ($|S_{11}| \leq -25$ dB) compared to horns A and B.

1.4.2 Radiation pattern measurements

The radiation pattern of the printed circular horns A, B, and C are measured using Keysight N9925A FieldFox vector network analyzer (VNA) and high-directivity circular horn antenna. The high-directivity circular horn with gain, $G \sim 18$ dBi is used as a transmit antenna (source). On the other hand, the printed circular horn under test is the receiving antenna. It should be noted that the transmitting and the receiving horns must have the same polarization characteristics (prefer, both are the same type of antennas) in order to avoid polarization mismatch, which can affect the accuracy of the radiation pattern measurement. The performance and specifications of the high-directivity circular horn is shown in Figs. 1.14 and 1.15. The half-power beam width (HPBW) of the high-directivity circular horn is nearly 12° and the front-to-back ratio (FBR) with average level of ~ 27.5 dB.

Before the radiation pattern is measured, the transmit power level is set to 0 dBm. Both antenna horns are fixed and supported by a tripod. The TRL calibration is performed on the waveguide adapters (at port-1 and port-2) before both horn antennas are connected to the adapters. Once the calibration process is completed, the high-directivity horn and the printed circular horn (horn A or B or C) are respectively connected to the adapters, and both horns are separated by a distance of ~ 1 m as shown in Fig. 1.16.

The printed circular horn is manually rotated from 0° to 360° , with an interval of 2.5° using the Ulanzi U-70 rotational platform, and the corresponding received signal, $|S_{21}|$ in unit dB, is measured as shown in Fig. 1.17. The measured $|S_{21}|$ values (normalized with its maximum $|S_{21}|$) varies with the angle, θ , and is plotted in polar form so that the radiation pattern for the horn under test (horn A or B or C) can be displayed and interpreted more clearly as illustrated in Fig. 1.18. The corresponding radiation pattern in the Cartesian plot is plotted in Fig. 1.19. Based on the measurement results, the HPBW and side-lobe level of the horns A, B, and C are tabulated in Tab. 1.5.

There is a deviation that occurs between the simulated and measured radiation patterns, which is due to line-of-sight misalignment between the high-directivity horn and the printed horn under test. In addition, the uncertainty of the rotation scale (manual rotation) of the horn under test can also lead to significant errors in radiation measurements.

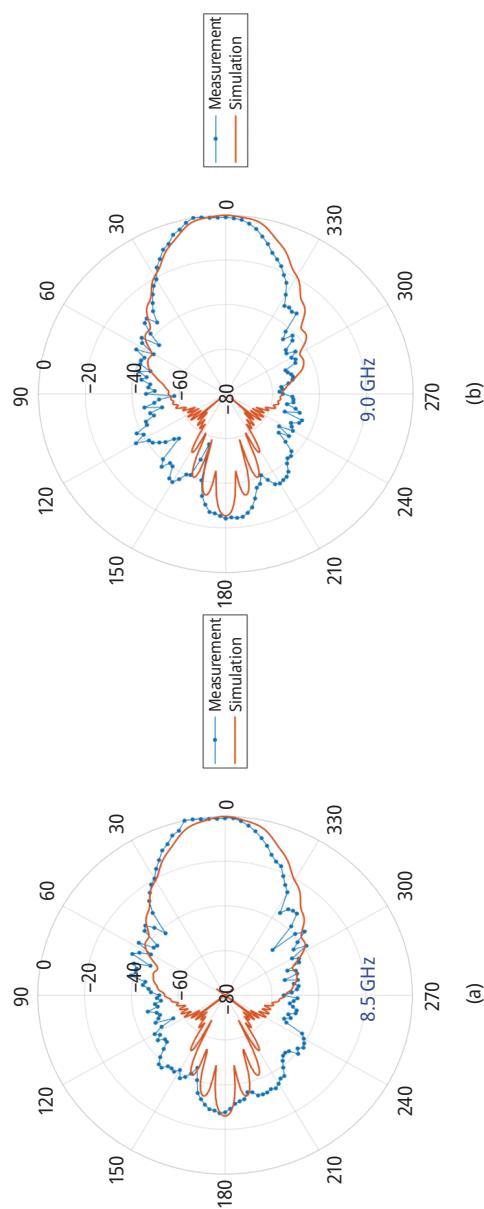


Fig. 1.14: Normalized radiation pattern of the high-directivity standard circular horn at (a) 8.5 GHz and (b) 9.0 GHz, respectively.

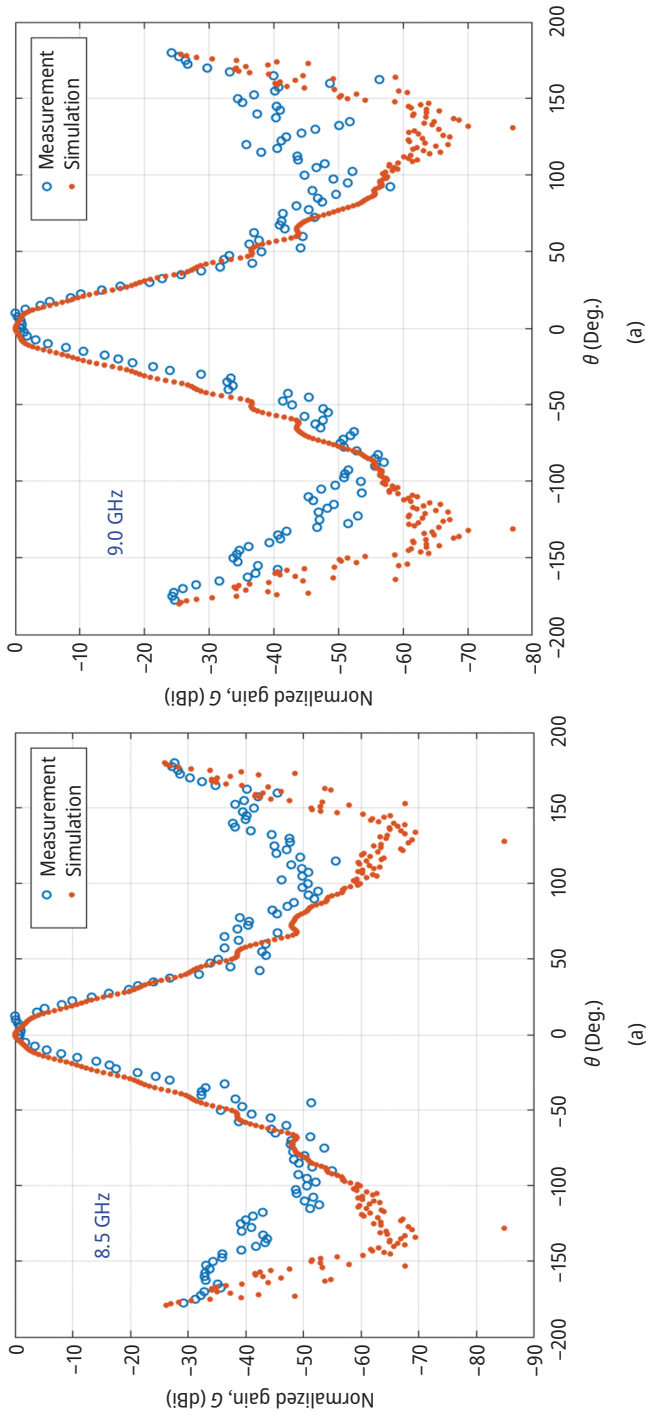


Fig. 1.15: Normalized gain G varies with angle θ at (a) 8.5 GHz and (b) 9.0 GHz, respectively.

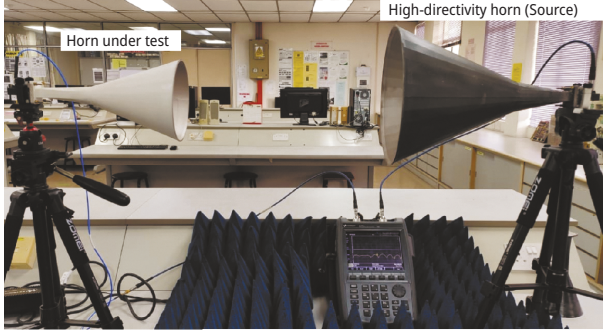


Fig. 1.16: Experiment setup.

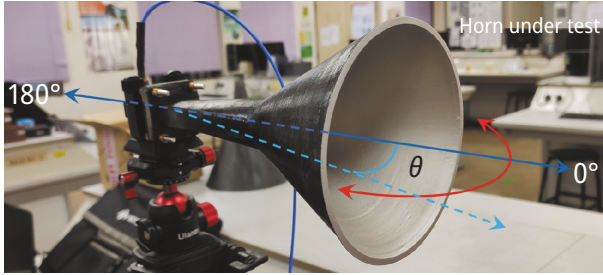


Fig. 1.17: The rotation direction of the radiation pattern.

1.4.3 Gain measurements

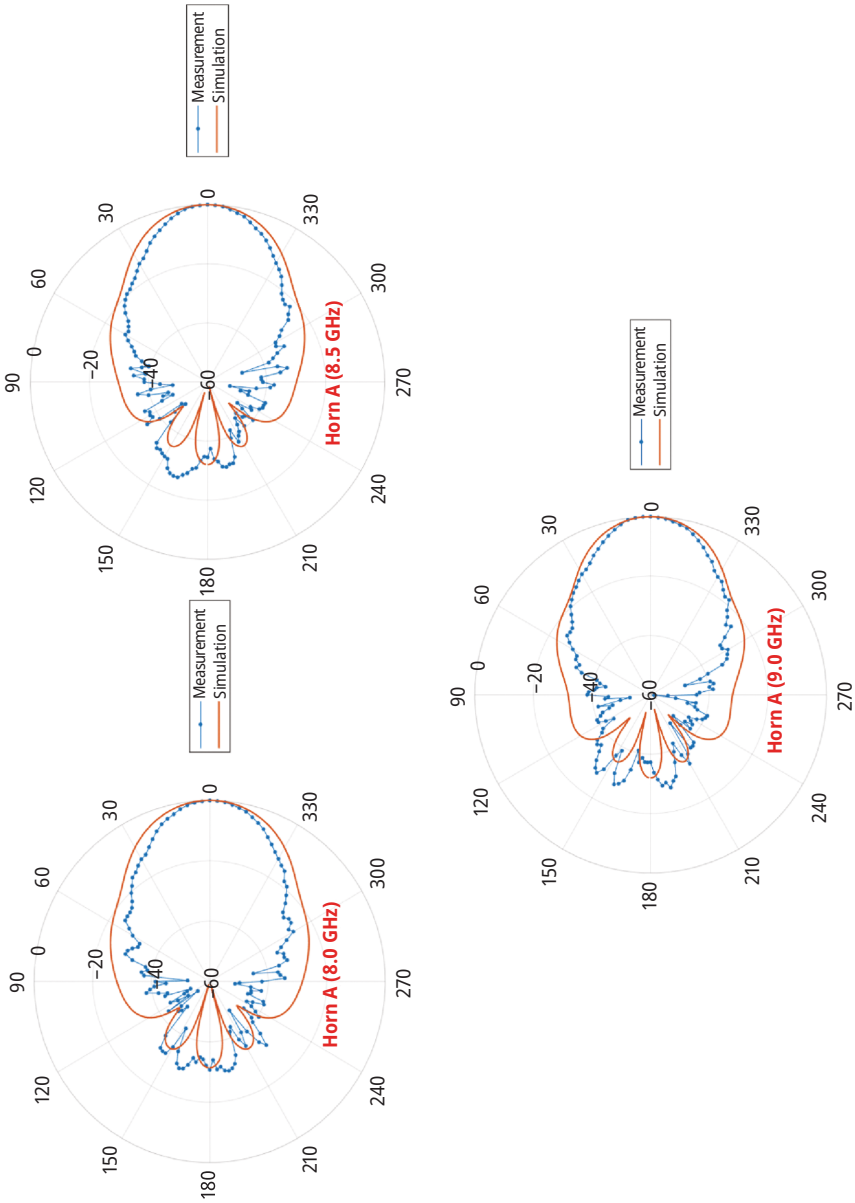
In this work, the gains G of the three circular horn antennas, namely, horn antennas A, B, and C, are verified and measured using the three-antenna method. Let G_A , G_B , and G_C denote the gains G of antennas A, B, and C, respectively. Using the three-antenna method, three combination sets of measurements are obtained and their corresponding Friis equations are given as [49]

$$G_A(\text{dB}) + G_B(\text{dB}) = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + P_{r_B} - P_{t_A} \quad (1.8)$$

$$G_B(\text{dB}) + G_C(\text{dB}) = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + P_{r_C} - P_{t_B} \quad (1.9)$$

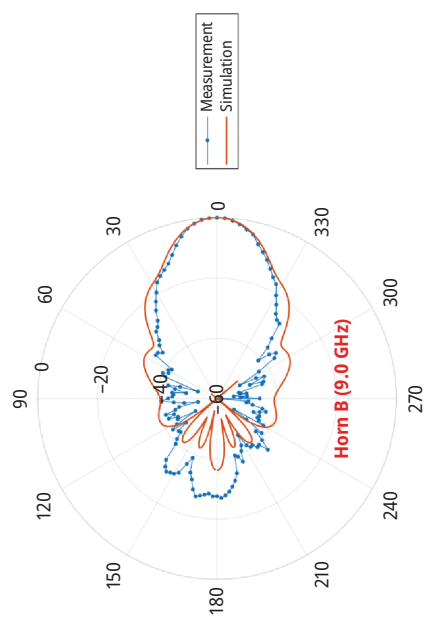
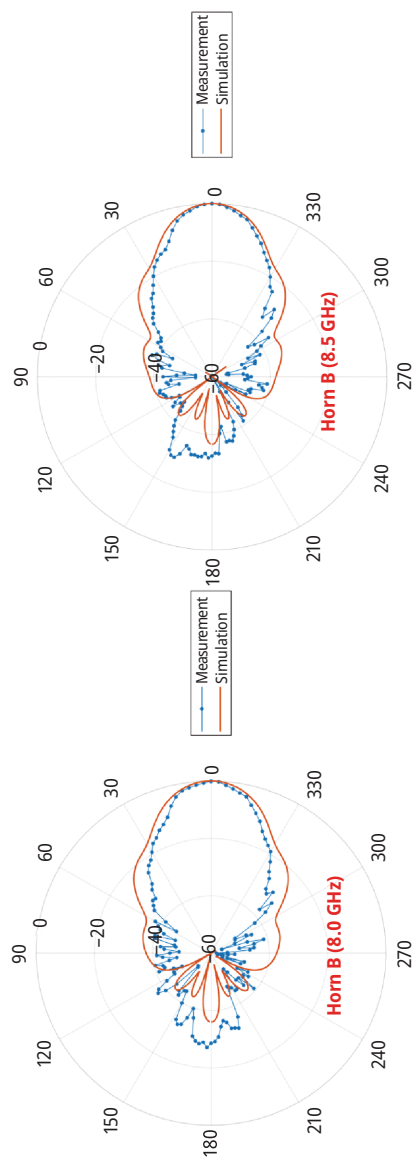
$$G_A(\text{dB}) + G_C(\text{dB}) = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + P_{r_A} - P_{t_C} \quad (1.10)$$

where P_{t_A} , P_{t_B} , and P_{t_C} are the measured transmitted powers when horns A, B, and C are used as transmit antennas, respectively. On the other hand, P_{r_A} , P_{r_B} , and P_{r_C} are the measured received powers when horns A, B, and C are the receiving antennas,



(a) Circular horn A

Fig. 1.18: Polar plots of the radiation patterns of circular horns A, B, and C, respectively.



(b) Circular horn B

Fig. 1.18 (continued)

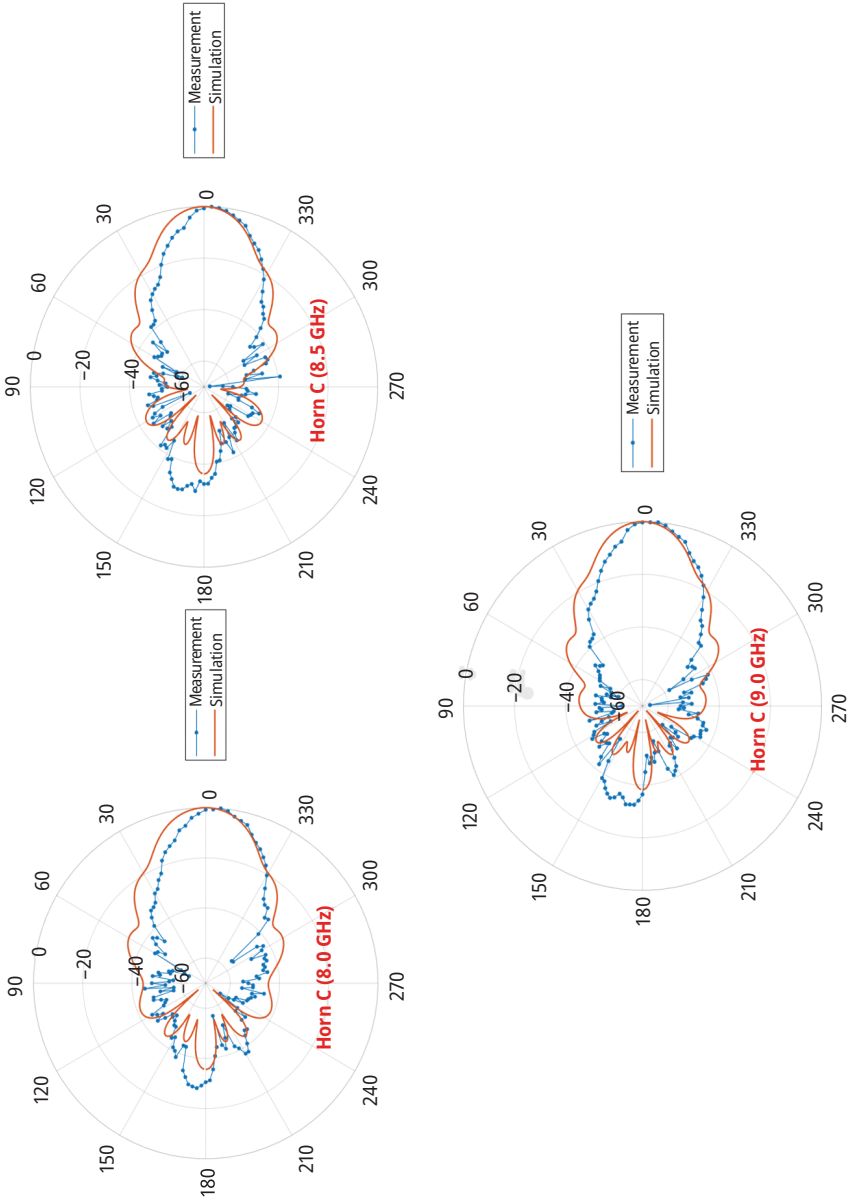


Fig. 1.18 (continued)

(c) Circular horn C

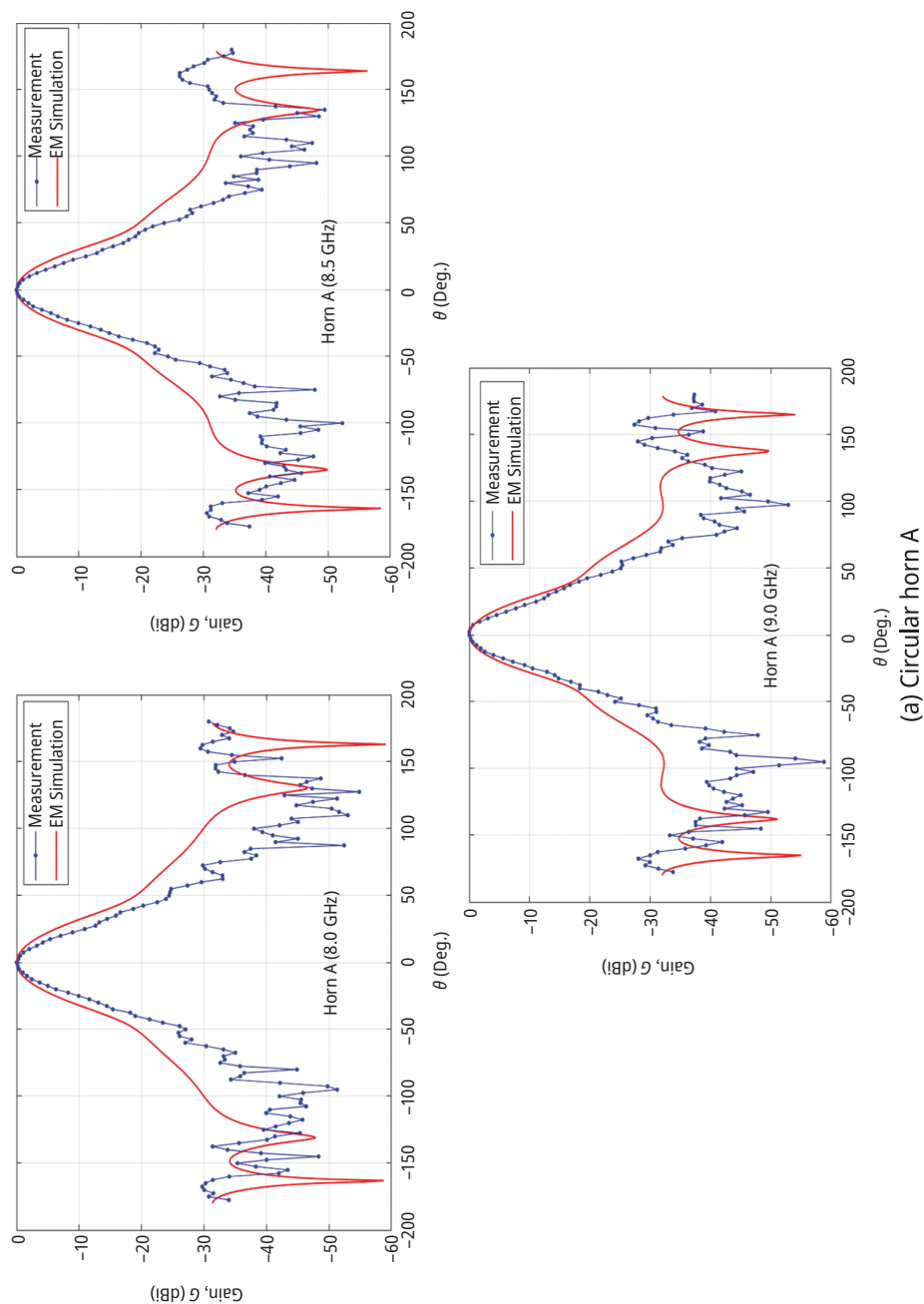


Fig. 1.19: Cartesian plots of the radiation patterns of the circular horns A, B, and C at 8.0 GHz, 8.5 GHz, and 9.0 GHz, respectively.

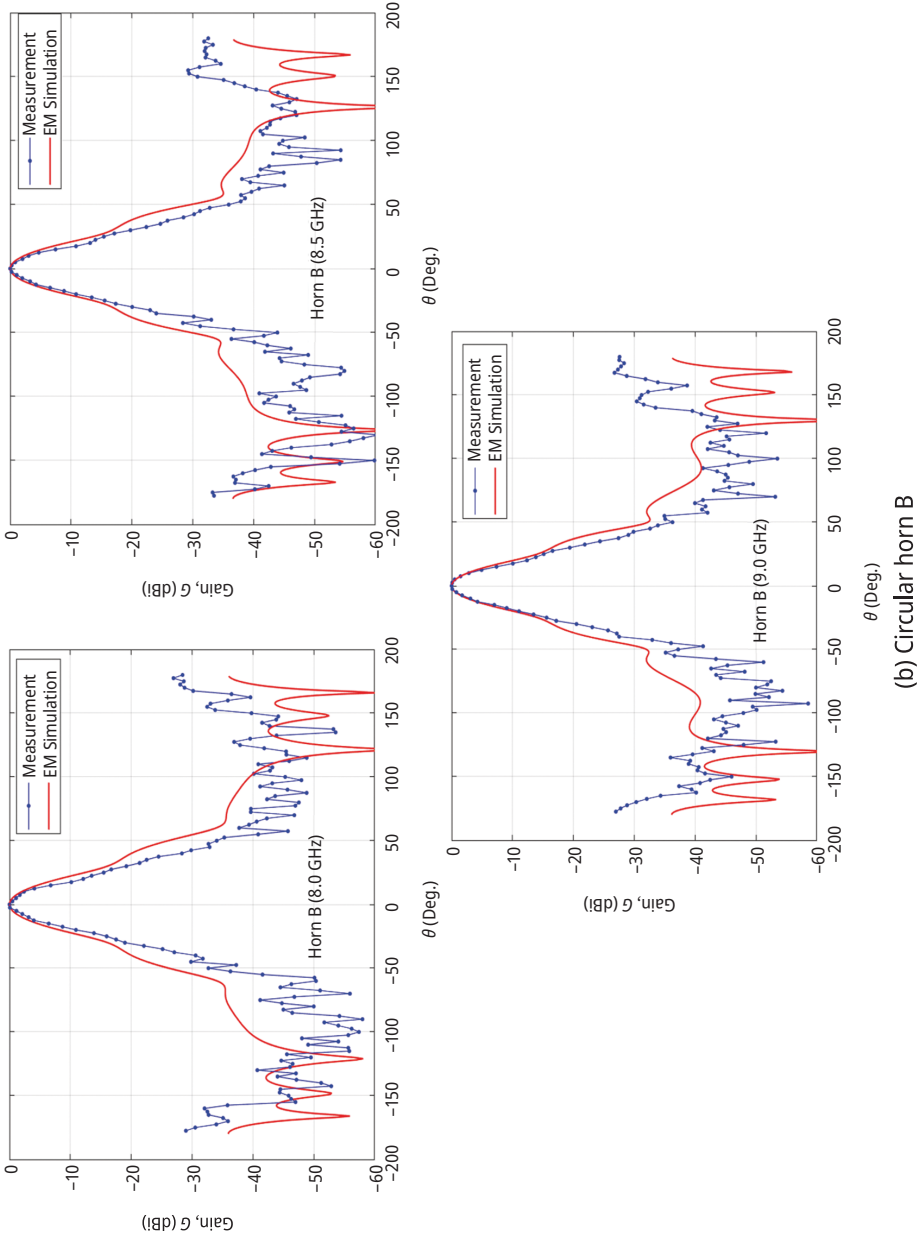
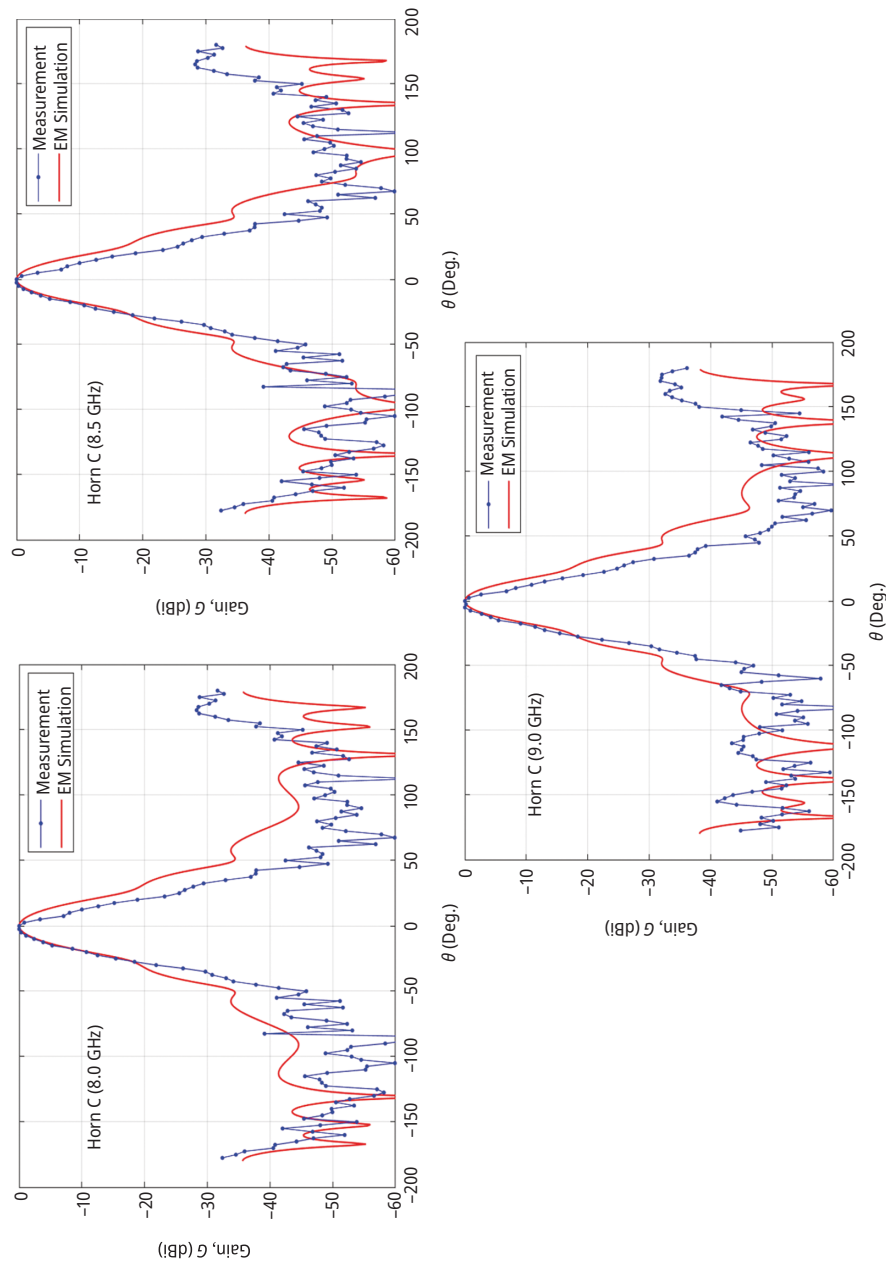


Fig. 1.19 (continued)



(c) Circular horn C

Fig. 1.19 (continued)

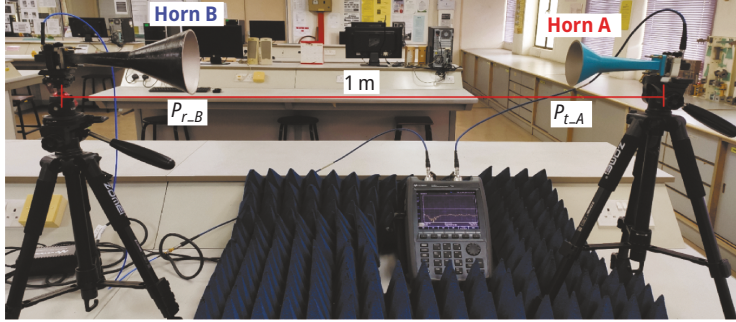
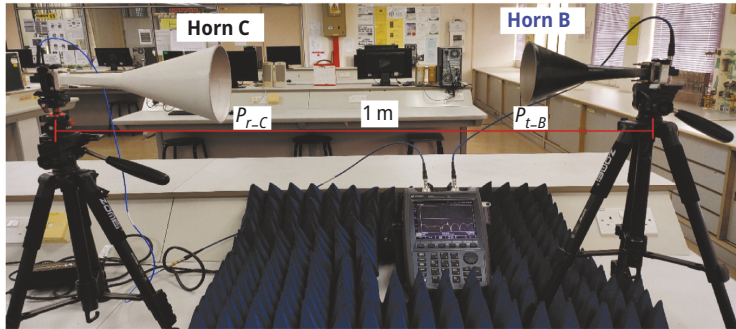
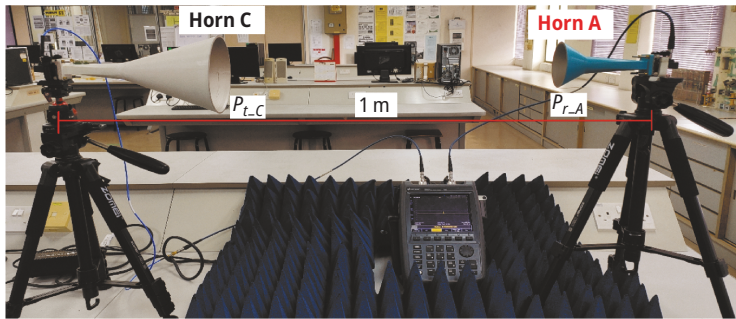
Tab. 1.5: Comparison between the simulated and measured gain, G of the printed circular horns A, B, and C.

Circular antenna	f (GHz)	HPBW (degree)		Side-lobe level (dB)	
		Simulation	Measurement	Simulation	Measurement
A	8.0	34.6	~27.5	-31.4	-29.4
	8.5	32.7	~27.5	-32.0	-26.2
	9.0	30.6	~27.5	-31.7	-27.4
B	8.0	24.3	~22.5	-35.5	-27.1
	8.5	22.8	~20.0	-34.2	-28.4
	9.0	21.4	~22.5	-32.0	-26.8
C	8.0	21.1	~17.5	-33.8	-28
	8.5	19.9	~17.5	-34.1	-29
	9.0	18.9	~17.5	-32.0	-32.1

respectively. The spacing d between the high-directivity horn (transmit antenna) and the horn under test (receive antenna) is 1 m. Due to the TRL calibration being done on the aperture adapter (connection junction between the adapter and the horn), a 1 m spacing between the antennas is considered, starting from the adapter at port-1 to the adapter at port-2.

The three combinations of measurement setups are shown in Fig. 1.20. The all transmitted powers ($P_{t_A} = P_{t_B} = P_{t_C}$) are fixed at 0 dB, while the received power P_r is equal to the measured insertion loss, $|S_{21}|$ in unit dB of horns A, B, and C using Keysight N9925A FieldFox VNA. The measured $|S_{21}|$ of the horns A, B, and C, with operating frequencies from 8 to 9 GHz, are illustrated in Fig. 1.21. Based on the measured $P_{t_A} = 0$ dB, $P_{t_B} = 0$ dB, $P_{t_C} = 0$ dB, $P_{r_A} = |S_{21A}|$ dB, $P_{r_B} = |S_{21B}|$ dB, and $P_{r_C} = |S_{21C}|$ dB, the (1.8), (1.9), and (1.10) can be solved simultaneously to obtain the gains (G_A , G_B , and G_C) of each of the antennas. The MATLAB code for computing the gains of antennas A, B, and C can be found in the **Appendix**.

Fig. 1.22 shows the variation in gain G of horns A, B, and C with operating frequency, f . As expected, the measured gain, G value of the horn A is close to 15 dBi since horn A was originally dimensioned, based on $G = 15$ dBi at 9 GHz. Likewise, the gains, G of horns B and C are approximately ~18 dBi and ~20 dBi, respectively. A comparison of the simulated and measured gains, G at 9 GHz for horns A, B, and C is presented in Tab. 1.6.

(a) P_{t-A} and P_{r-B} measurements(b) P_{t-B} and P_{r-C} measurements(c) P_{t-C} and P_{r-A} measurements**Fig. 1.20:** Three-antenna method measurement setup.

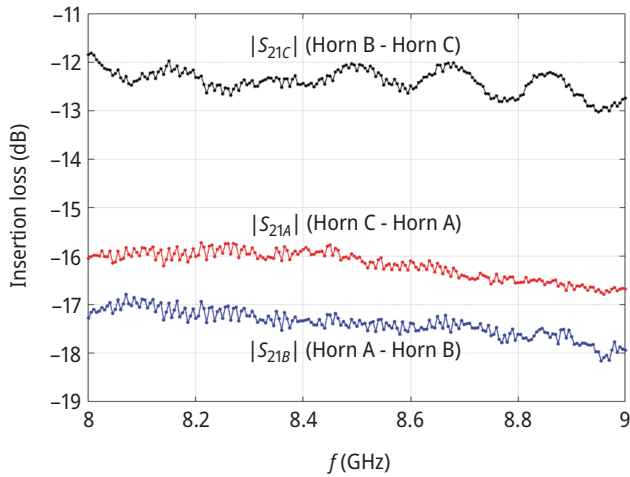


Fig. 1.21: Insertion loss $|S_{21}|$ (dB) versus operating frequency, f .

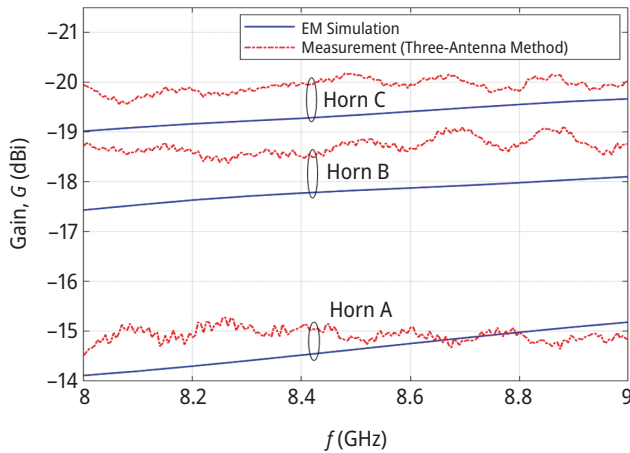


Fig. 1.22: Gain G of the circular horn antennas versus operating frequency, f .

Tab. 1.6: Comparison between the simulated and measured gain G of the printed circular horns A, B, and C.

f (GHz)	Antenna	Gain G (dBi)		
		Desired value	EM simulated value	Three-antenna measurement method
9.0	A	15.0	15.184	14.832
	B	18.0	18.103	18.764
	C	20.0	19.665	20.025

1.5 Conclusion

This chapter has successfully demonstrated the process and considerations for building an antenna using fused deposition modeling. Four 3D-printed circular horns, operating at X-band frequency, are printed, fabricated, and their return loss, $|S_{11}|$, radiation pattern, and maximum gain, G are measured using the vector network analyzer.

The performances of the 3D-printed circular horns are consistent with the simulation results, in which the material of the horn in the simulation is a metallic material. This 3D printing technology with auxiliary metal coating is low in cost and light in weight, which is suitable for engineering design practice in universities, especially for undergraduate students.

Currently, 3D printers can be purchased for a few hundred dollars, compared with 10 years ago – the price of the cheapest 3D printer then was nearly 2,000 USD. In addition, the volume size for 3D printers is increasing. In the future, high-resolution and high-precision 3D printers will be commonly used (used together with 3D image scanners) and will become domestic devices in homes and offices.

Appendix (MATLAB program: circular horn design calculation)

```
close all;
clear all;

% Height, a (m) and width, b (m) of the rectangular aperture
a = 0.01016;
b = 0.02286;

% Diameter, d (m) of the circular aperture
d = 0.023825;

% Antenna gain in unit dB
GdB = 15;

% Speed of light in free space (m/s)
c = 299792458;

% Antenna gain in linear magnitude
G = 10.^(GdB./10);

% Center operating frequency (Hz)
f = 10e9;
```

```

% Find axial length (m) [Equation(3)]
L = (c./f).*(0.062598201.*G-0.10772524)

% Find diameter, D of the circular horn aperture (m) [Equation (5)]
fn=@(D)(0.322831441824362.*(f./c).*D.^2- . . .
0.04038209941846271.*D-0.02230999881063418.*(c./f))-L

D=fzero(fn,[0.0001, 5])

% Axial length, l from circular waveguide junction to horn aperture (m)
[Equation (6)]
l=L.*(1-(d./D))

```

Appendix (MATLAB program: three-antenna gain calculation)

```

close all;
clear all;

% Transmit power of antenna A (dBm)
PtA=0;
% Receive power of antenna B (dBm)
PrB=Data(:,2);

% Transmit power of antenna B (dBm)
PtB=0;
% Receive power of antenna C (dBm)
PrC=Data(:,3);

% Transmit power of antenna C (dBm)
PtC=0;
% Receive power of antenna A (dBm)
PrA=Data(:,4);

% Distance between transmit and receive antennas (m)
d=1;

% Operating frequency (Hz)
f=9e9;

% Equations (8), (9), and (10)
GAB=20.*log10(4.*pi.*f.*d./299792458)+PrB-PtA;

```

```
GBC = 20.*log10(4.*pi.*f.*d./299792458) + PrC-PtB;
GCA = 20.*log10(4.*pi.*f.*d./299792458) + PrA-PtC;
```

```
% Gain of antenna B (dBi)
```

```
GB = 0.5.*(GAB-GCA + GBC)
```

```
% Gain of antenna A (dBi)
```

```
GA = GAB-0.5.*(GAB-GCA + GBC)
```

```
% Gain of antenna C (dBi)
```

```
GC = GCA-GA
```

Abbreviation

3D	Three-dimensional
ABS	Acrylonitrile butadiene styrene
CST	Computer simulation technology
DLP	Digital light processing
EM	Electromagnetic
FBR	Front-to-back ratio
FDM	Fused deposition modeling
HPBW	Half-power beamwidth
IEEE	Institute of Electrical and Electronics Engineers
MATLAB	Matrix Laboratory
MDPI	Multidisciplinary Digital Publishing Institute
PA	Polyamide/nylon
PBF	Powder bed fusion
PC	Polycarbonate
PETG	Polyethylene terephthalate glycol
PLA	Polylactic acid
PVA	Polyvinyl alcohol
SLA	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering
STL	Standard Tessellation Language
TPU	Thermoplastic polyurethane
TRL	Through-reflect-line
UV	Ultraviolet
VNA	Vector network analyzer
VSWR	Voltage standing wave ratio
WoS	Web of Science

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Purnima Sharma, Satyajit Anand and Vikrant Sharma

2 The recent developments in 3D bioprinting: a general bibliometric study and thematic investigation

Abstract: This chapter presents an analysis of biomaterial-based three-dimensional (3D) bioprinting technology for fabricating tissues. In this study, the advances in 3D bioprinting are analyzed bibliometrically and thematically. A literature search was carried out on the Scopus database for documents related to biomaterial-based 3D bioprinting. To conduct this study, a total of 1,053 research articles from 2012 to March 2023 were reviewed. Bibliometrix (R package) and SciMAT tools were used to conduct this review in terms of bibliometric and thematic analysis. The analysis presents results such as contributing authors and coauthors, main affiliations, leading contributing countries, main relevant sources, and major themes. The derived results provide insights into the limitations and scope of collaborative research in the area of 3D bioprinting using biomaterials. In terms of publications and citations, the top three contributing countries are the USA, China, and Canada. It appears that 3D bioprinting for tissue engineering is a growing area of exploration. This chapter also explores the role of artificial intelligence in 3D bioprinting. The present study is the first to analyze the current state evaluation of 3D bioprinting.

Keywords: Bibliometric, bioinks, biomaterial, bioprinting, tissue, thematic analysis

2.1 Introduction

Bioprinting, also known as three-dimensional printing, is considered the technology most likely to lead to medical breakthroughs and solve complex medical issues [1]. Through 3D bioprinting, researchers can produce artificial organs that completely replace damaged organs, allowing for faster translational research [2]. The application

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of 3D bioprinting technology has become widespread, for example, in cell engineering, disease studies, and drug development [3]. In the early 1980s, engineer Charles Hull proposed the concept of additive manufacturing, also known as 3D printing, which has been translated into healthcare over the past few years under regulatory guidance [4]. 3D bioprinting involves printing cells or biomolecules on a substrate in an arrangement that allows the cells to bind together and form a 3D structure [5]. 3D printing, used in tissue engineering, is an important method for fabricating complex three-dimensional printed constructs using biocompatible materials, cells, and supporting components [6]. Through bioprinting, highly mimicked tissues and organs can be fabricated [7]. Global organ shortages have driven the field of tissue engineering, particularly the development of microenvironments for the regeneration of skin, cartilage, bone, ligaments, and cardiac tissues [8].

Compared to manual tissue culture, 3D bioprinting offers better spatial control and precise cell patterning. Researchers have been able to precisely reproduce cell populations, bio-microenvironments, organ microarchitectures, and tissue functions in a wide variety of tissues using suitable printing techniques and biomaterials. These tissues include the heart, kidney, liver, and muscle, and will continue to expand with advances in research [9]. In recent years, technology has advanced to create 3D cardiac constructs that can be used to treat myocardial infarctions and associated complications [10]. Scientists have also discovered that 3D printing constructs derived from stem cells can generate replicas of diseased and healthy tissues, as well as replacements for diseased and impaired tissues [11]. In bioprinting and tissue engineering, particularly in the redevelopment of bone tissue, it is crucial to develop bioinks that have suitable printability and specific bioactivities. Encouraging progress has been made in the creation of three-dimensional cardiac tissue, suggesting that it could be a potential alternative to heart transplantation [11].

The most commonly used 3D bioprinting methods can be categorized as jetting-based [12], extrusion-based [13], and laser-assisted [14] bioprinting. Each of these methods can be further classified into subcategories based on their specific working principles. In extrusion-based bioprinting, the bioink can be extruded onto the stage using either air pressure or mechanical means. In inkjet-based bioprinting, the droplet is separated from the main ink reservoir by creating an air bubble using thermal or piezoelectric methods. Laser-assisted bioprinting relies on the use of a laser beam. Over the past five years, extrusion-based bioprinting has experienced significant growth in research, while laser-assisted bioprinting has shown a decline in popularity. Inkjet-based bioprinting, on the other hand, has remained relatively stable in terms of its popularity and usage.

2.2 Biomaterials and bioprinting: literature review

Biomaterials are currently the focus of extensive research for manufacturing structures using 3D bioengineering. A 3D printer builds objects by layering materials one after another [15]. For 3D bioprinting, a material should have characteristics such as printability, extensibility, and biocompatibility [16]. Biomaterials are used as the microenvironment for living cells in bioprinting. Often referred to as bioinks, these materials are derived from hydrogel precursors, which gel in a way that allows them to be used in bioprinting procedures [17]. Bioink selection is a function of the manufacturing process, biological function, and other physiological aspects [18]. The intrinsic properties and flexibility of carbon materials have recently sparked interest in combining them with hydrogels for the growth of advanced materials with biomedical uses [19]. Carbon nanotubes, due to their outstanding thermal and mechanically stable properties and conductivity are found to be perfect for biomedical applications [20].

Hydrogels have numerous benefits in biofabrication, tissue engineering, and organ engineering. Biomimetic materials based on nature-derived architectures, which create porous implants, provide the basis for bioprintable metamaterials [21]. Metamaterials with mechanical properties have also been used to develop fundamental designs for operational tissue scaffolds, showing promise for use in bone tissue redevelopment and orthopedic transplants. The advantages and applications of popular marine materials such as alginate, collagen, carrageenan, chitosan, hyaluronic acid, and gelatin (GEL) for 3D bioprinting are discussed in [22]. To fabricate flexible and biocompatible boards, nanoparticle silver is infused between two GelMA layers and used to print electronic circuitry [23]. Various biofabrication technologies, including microfluidics and layered assembly, can be used to create microstructures within scaffolds [24].

Currently, bioprinted tissues have limited functionality and scalability because they are generally small and composed of few types of cells [25]. The limited printing space of 3D printers restricts the size of tissues that can be created and the ability to print whole organs. There are two categories of challenges faced by bioprinting: one category involves the development of bioinks suitable for different tissues, and the other category deals with regulatory challenges [26]. Therefore, the potential of bioprinting can only be fully realized through advancements in both biomaterials and bioprinting systems [27]. In [28], 3D bioprinting techniques for plastic surgery are discussed in terms of their advantages, disadvantages, and challenges.

Synthetic polymers like polycaprolactone, polylactide, and polyurethane can be used in the preparation of biomaterial inks. Several natural biopolymers are promising options for preparing biomaterial inks, including alginate (Alg) and collagen (COL), which are found in human connective tissue. GEL, a derivative of COL is also a viable option. An overview of the characteristics and applications of sodium alginate (SA) hydrogel for tissue engineering is presented in [29]. SA-based hydrogels in 3D bioprinting can achieve soft tissue repair and regeneration. In [30], a biocompatible material for wearable electronics is developed by functionalizing GEL-based bioink with

choline bioionic liquid. This programmable polymer exhibits flexibility, transparency, and excellent ion conductivity.

An analysis of the biochemical and morphological changes in extracellular matrix (ECM) properties in different tissues and organs in healthy and pathological states is presented, along with how ECM mimics can be generated using 3D printing in [31]. The complexity of lung structure and architecture is highlighted as a key challenge in lung tissue bioprinting [32]. In order to design lung tissues that can be transferred into patients, multifunctional biomaterial inks must be developed. Smart biocompatible materials encapsulate and deliver healing charges on-demand to specific sites based on their surrounding physiological changes [33]. In recent years, multilayer hydrogels have become a good delivery system for drugs. The electrospinning approach in 3D bioprinting enables the design of smart hydrogels for usage in drug delivery and tissue development. An effective method for rebuilding bulky solid organs is to use 3D bioprinting technology combined with decellularized extracellular matrices (dECM) [34]. dECMs are among the most rapidly expanding bioactive printing materials and play a critical role in cell-based 3D bioprinting. The outcomes of biomaterials and 3D bioprinting research are shown in Tab. 2.1.

Tab. 2.1: Outcomes of biomaterials and 3D bioprinting research.

Outcome	Source
3D printers build objects by layering materials one after another.	[15]
Characteristics required for 3D bioprinting materials include printability, extensibility, and biocompatibility.	[16]
Biomaterials, referred to as bioinks, are used as the microenvironment for living cells in bioprinting.	[17]
Bioink selection depends on the manufacturing process, biological function, and physiological aspects.	[18]
Carbon materials combined with hydrogels for advanced biomedical materials.	[19]
Carbon nanotubes have outstanding properties for biomedical applications.	[20]
Biomimetic materials based on nature-derived architectures create porous implants.	[21]
Popular marine materials like alginate, collagen, carrageenan, chitosan, hyaluronic acid, and GEL for bioprinting.	[22]
Nanoparticle silver infused between GelMA layers for flexible and biocompatible boards.	[23]
Various biofabrication technologies, including microfluidics and layered assembly, create microstructures.	[24]
Bioprinted tissues have limited functionality and scalability.	[25]

Tab. 2.1 (continued)

Outcome	Source
Challenges in bioprinting include developing suitable bioinks and dealing with regulatory challenges.	[26]
Advancements in biomaterials and bioprinting systems are necessary for using the potential of bioprinting.	[27]
3D bioprinting techniques for plastic surgery are discussed in terms of advantages, disadvantages, and challenges.	[28]
SA hydrogel is suitable for tissue engineering in 3D bioprinting.	[29]
GEL-based bioink functionalized with choline bioionic liquid for biocompatible material in wearable electronics.	[30]
ECM mimics can be generated using 3D printing to mimic biochemical and morphological changes in tissues and organs.	[31]
Lung tissue bioprinting requires multifunctional biomaterial inks due to the complexity of lung structure.	[32]
Smart biocompatible materials encapsulate and deliver healing charges on-demand.	[33]
3D bioprinting combined with decellularized extracellular matrices is effective for rebuilding bulky solid organs.	[34]

The study describes the contributions of researchers around the world working in the domain of 3D bioprinting techniques for producing tissues and cells, while also providing direction for researchers interested in exploring this emerging area. The chapter aims to answer the following research questions:

- Q1: What is the evolution of articles on bioprinting using biomaterials?
- Q2: Which journals are the most renowned in this field?
- Q3: Who are the most notable authors in this field?
- Q4: What is the country-specific collective research scenario? Which organizations and countries have published the most research articles?
- Q5: What is the research focus of researchers in this field?

The chapter is organized as follows: Section 2.3 explains the data type collected from the Scopus database and presents the flow diagram of the entire process. The results and discussion of the bibliometric analysis are highlighted in Section 2.4. Thematic analysis outcomes are explained in Section 2.5 followed by conclusions in Section 2.6.

2.3 Data source and methodology

We collected articles on bioprinting using biomaterials from the Scopus database between 2012 and March 2023 to find answers to the questions posed in the Introduction section. The key search terms used were biomaterials and 3D bioprinting. The collected data was analyzed using the Bibliometrix tool. During the bibliometric mapping analysis, data were collected, extracted, filtered, and synthesized. For this study, data from the Scopus database were exported in BibTex format, which was then imported into the "Biblioshiny" tool of the Bibliometrix package [35]. It has been found that a total of 1,053 documents comprising 462 articles, 6 books, 42 conference papers, 1 conference review, and 435 review papers were published in 381 different sources. It is found that the average number of publications each year is 3.12. Table 2.2 describes the main characteristics of the collected data, while Tab. 2.3 lists the types of data. The main information about the data is given below.

Tab. 2.2: Main information about data.

Description	Value
Time duration	2012: March 2023
Sources (journals, books, etc.)	381
Total documents	1,053
Document average age	3.12
Annual growth rate %	34.47
References	95,108
Average citations per document	44.41

Tab. 2.3: Type of documents.

Document types	No. of articles
Article	462
Book	6
Book chapter	97
Conference review	1
Conference paper	42
Erratum	2
Editorial	4
Review	435
Short survey	3

The exported data consists of the following information: (a) authors, (b) title, (c) source title, (d) publisher information, (e) abstract, (f) author keywords, (g) publication year, (h) affiliation, (i) ISSN/ISBN, (j) languages, (l) DOI, and (m) funding agencies. These data provide comprehensive details for analysis in the emerging field of bioprinting using bioma-

terials. Bibliometric analysis is employed to analyze the recent developments in this area. The study presents results based on the top contributing countries, active affiliations, top relevant keywords, and authors who have contributed to and published in this domain. Visualizations of the results are extracted from the Biblioshiny tool. Figure 2.1 illustrates the flow diagram of the entire process, which includes data collection from the Scopus database, filtering and processing using the Bibliometrix R package and SciMAT. The processed results are presented in the form of figures and tables, providing a clear and concise overview of the findings.

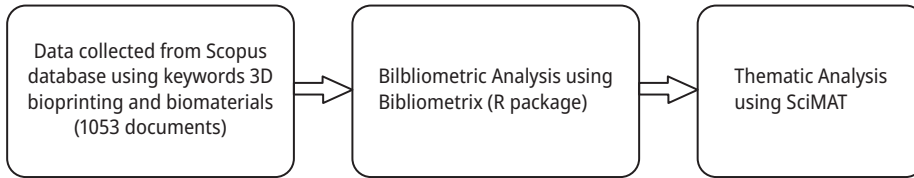


Fig. 2.1: Flow diagram of the analysis process.

2.4 Outcomes and discussion: bibliometric analysis

In this section, we provide results of bibliographic analysis and provide an analysis of research documents available from 2012 to March 2023.

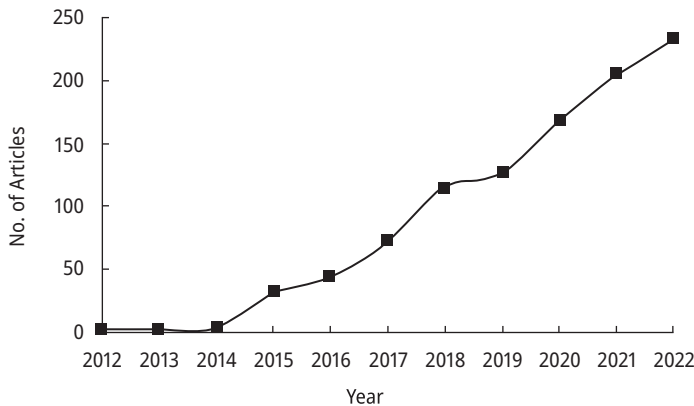


Fig. 2.2: Annual production plot.

Figure 2.2 illustrates the distribution of publications in the field of bioprinting between 2012 and 2022. The figure indicates a steady increase in research articles since 2014. In 2022, there was a peak with 232 publications (Q1). As of March 2023, 52 additional papers have been published, indicating ongoing research in the field.

Recent research has primarily focused on three main areas, as highlighted in the figure: optimizing 3D bioprinting using bioinks, fabricating biomaterials for surgical procedures, and optimizing 3D bioprinting through the use of machine learning techniques.

Figure 2.3 showcases the diverse range of sources that publish research articles related to bioprinting. The *Biofabrication* journal stands out with the highest number of papers, having published 50 articles and achieving an h-index of 27. Additionally, a significant number of research papers are published in journals that specialize in biomaterials, healthcare, and the latest trends in biotechnology and biofabrication (Q2).

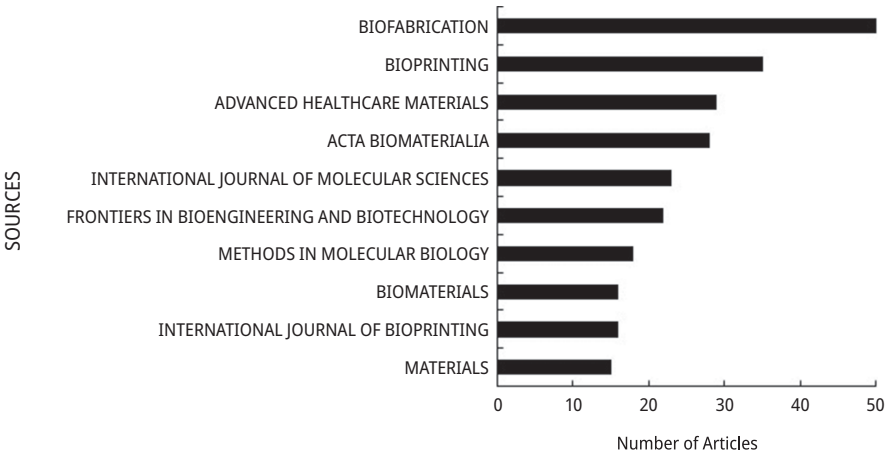


Fig. 2.3: Top 10 sources that published articles in the research field.

Table 2.4 summarizes information about the contribution of authors to bioprinting publications.

Tab. 2.4: Main information about contributing author.

Authors	3,923
Authors of single-authored documents	29
Collaboration between authors	
Documents (single-authored)	32
Coauthors per document	5.57
International coauthorships %	28.68

Figure 2.4 presents the key authors contributing to the field of bioprinting (Q3). Xiaohong Wang from the Department of Mechanical Engineering at Tsinghua University in Beijing, China, and Yaoyao Zhang from the Department of Obstetrics and Gynecology at the Reproductive Medical Center, West China Second University Hospital, Sichuan University, Chengdu, China, have made significant contributions with the highest

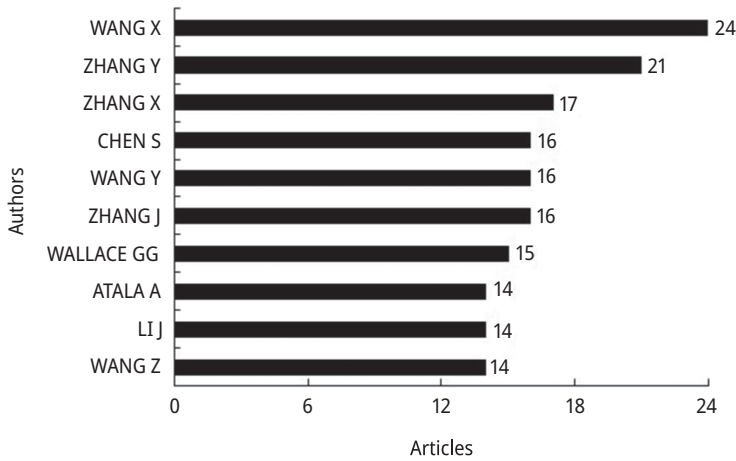


Fig. 2.4: Top 10 contributing authors with minimum 14 publications.

number of publications in the field. Anthony Atala, the inventor of the first 3D organ printer known as the Integrated Tissue and Organ Printing System, is recognized as one of the most important researchers in the organ printing field.

Furthermore, based on local citations, Michael Gelinsky, Sijia Liu, and Tilman Ahlfeld are the top three authors with 482, 450, and 428 citations, respectively. Their impactful contributions have been widely recognized in the field.

Figure 2.5 displays researchers from various organizations who have contributed significantly to the field of bioprinting. Among the 10 outstanding organizations, the University of California stands out with 96 research articles, indicating their leadership in the field.

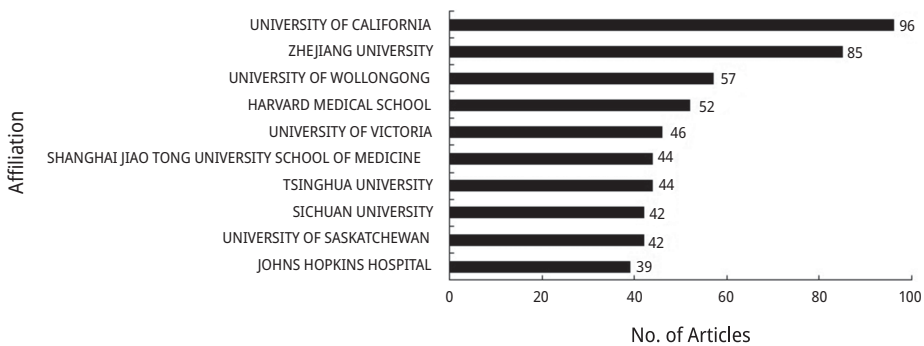


Fig. 2.5: Top 10 contributing affiliations worldwide.

The top-cited countries are depicted in Fig. 2.6. The USA leads with an average of 104.8 citations, followed by China and Canada (Q4). Among the countries, the USA and China have more than 100 publications each. The USA has a total of 189 publications, with 19,809 citations from these publications, ranking at the top of the list of the most productive countries. China follows closely with 185 publications, while Canada and Korea are the next most productive countries.

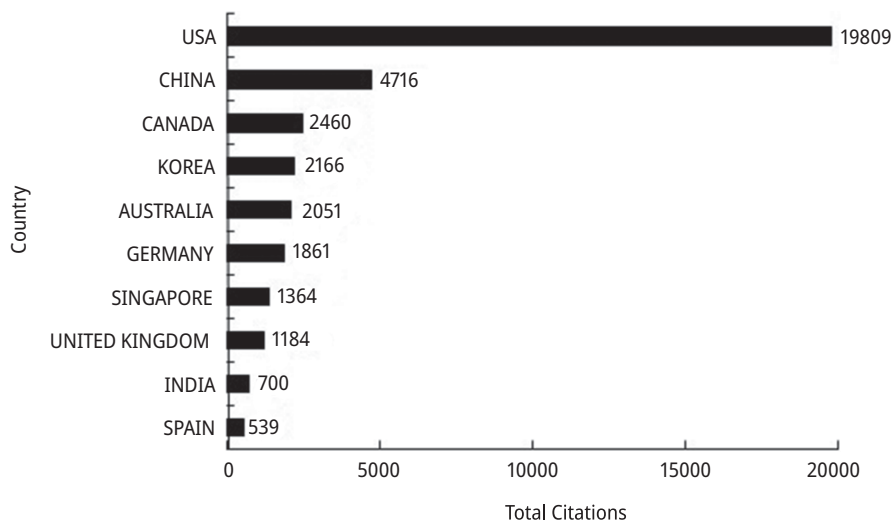


Fig. 2.6: Top 10 contributing countries.

The collaborative research between countries with respect to number of documents is presented in Fig. 2.7 and summarized in Tab. 2.5.

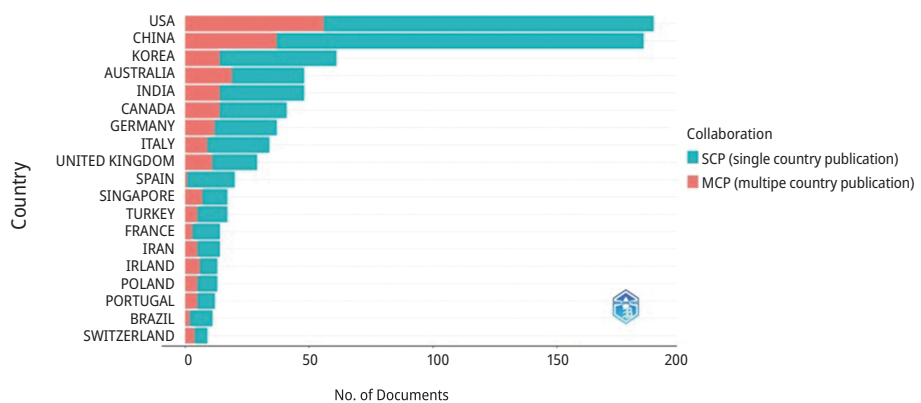


Fig. 2.7: Country-specific collaboration in research.

It can be seen that majority of countries focus on independent research, and domestic collaborations outnumber international collaborations. Researchers should work to expand bilateral cooperation and joint publications in the future.

Tab. 2.5: Collaboration between countries in research.

Country	No. of articles	Frequency	SCP	MCP	MCP_ratio
USA	189	133	56	0.179	0.296
China	185	148	37	0.176	0.2
Korea	149	118	31	0.142	0.208
Australia	61	47	14	0.058	0.23
India	48	29	19	0.046	0.396
Canada	48	34	14	0.046	0.292
Germany	41	27	14	0.039	0.341
Italy	37	25	12	0.035	0.324
United Kingdom	34	25	9	0.032	0.265
Spain	29	18	11	0.028	0.379

During the study it was found that most frequently used keywords are bioprinting, tissue engineering, 3D printer, and biomaterial (Q5). The occurrences of 10 frequently used keywords in the bioprinting research are presented in Fig. 2.8.

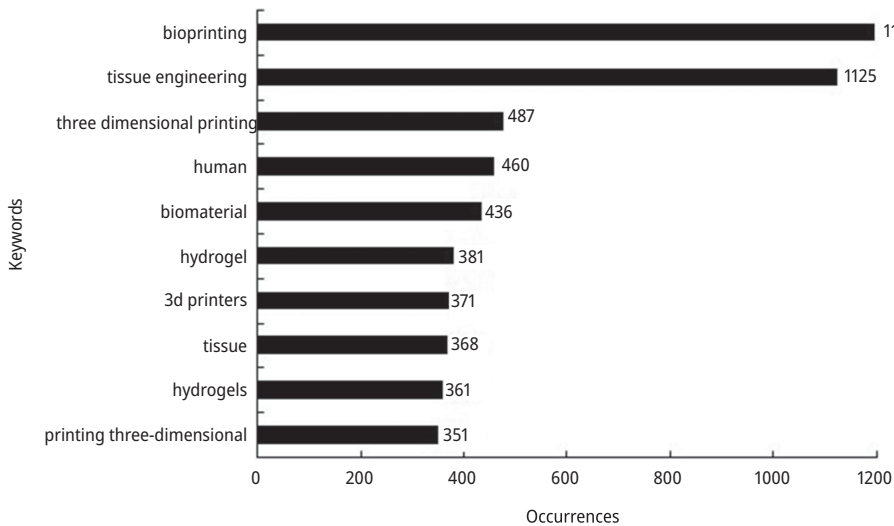


Fig. 2.8: Most frequently used keywords.

The most regularly used keywords in 3D bioprinting in the co-occurrence network are highlighted in Fig. 2.9. This figure shows the relationship between the keywords in three different clusters.

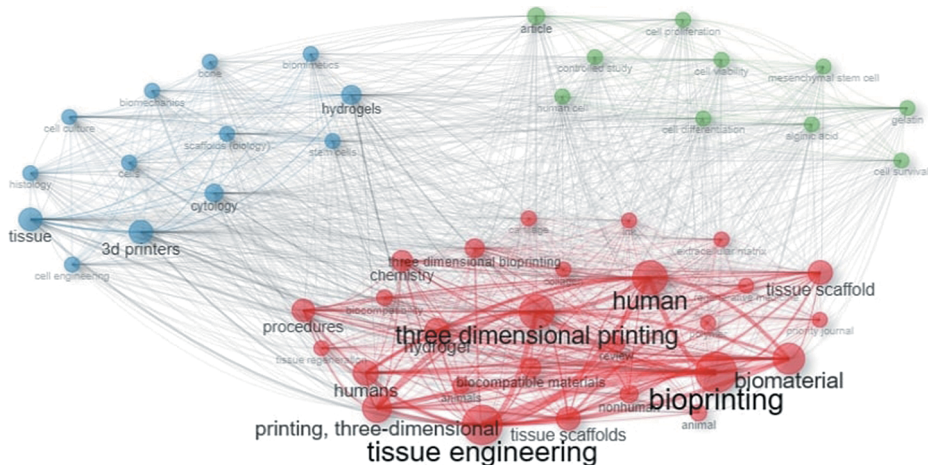


Fig. 2.9: Co-occurrence network of author's keywords.

2.5 Thematic analysis of 3D bioprinting

Thematic analysis is a qualitative method of analyzing data. The SciMAT tool allows researchers to explore science mapping within a longitudinal structure [36]. In SciMAT, the major themes are visualized in two ways, thematic networks and strategic diagrams [37]. Two-dimensional strategic diagrams consist of four quadrants, where density is represented by the vertical axis and centrality is represented by the horizontal axis. The centrality of a theme reflects the degree of interaction between them, while the density measures the strength among them. Four major clusters of research themes have been identified: motor themes (which are major driving themes and critical); highly developed and isolated themes (which are well-developed, but less critical); developing and declining themes (which are developing or diminishing); and basic and transversal themes (which are relevant for the present research, but not fully developed) [38].

The entire period 2012–March 2023, for the study of the scientific evolution of bioprinting using biomaterial, is divided into two phases: 2012–2019 and 2020–2023. This unequal periodization is based on two reasons: (a) to have about the same number of papers in both phases and (b) to understand the research trend before and after Covid-19. There are a number of documents published in each theme, which determines the nodal size in thematic evolution. The links indicate co-occurrences between

the clusters of different periods. Clusters with solid lines share the same themes, whereas clusters with dashed lines have different themes.

2.5.1 First period (2012–2019)

The strategic diagram in Fig. 2.10 depicts a total of 10 themes that were used out of which four are the motor themes. The three-dimensional printing, article, and tissue themes are well-developed, highly connected and have the maximum number of documents in comparison to the others (Q5). Physiology is developed but isolated from other themes related to bioprinting. Bioinks, 3D printing, and cartilage, which is a flexible connective tissue, are developing themes. Biocompatibility is the basic theme that is rel-

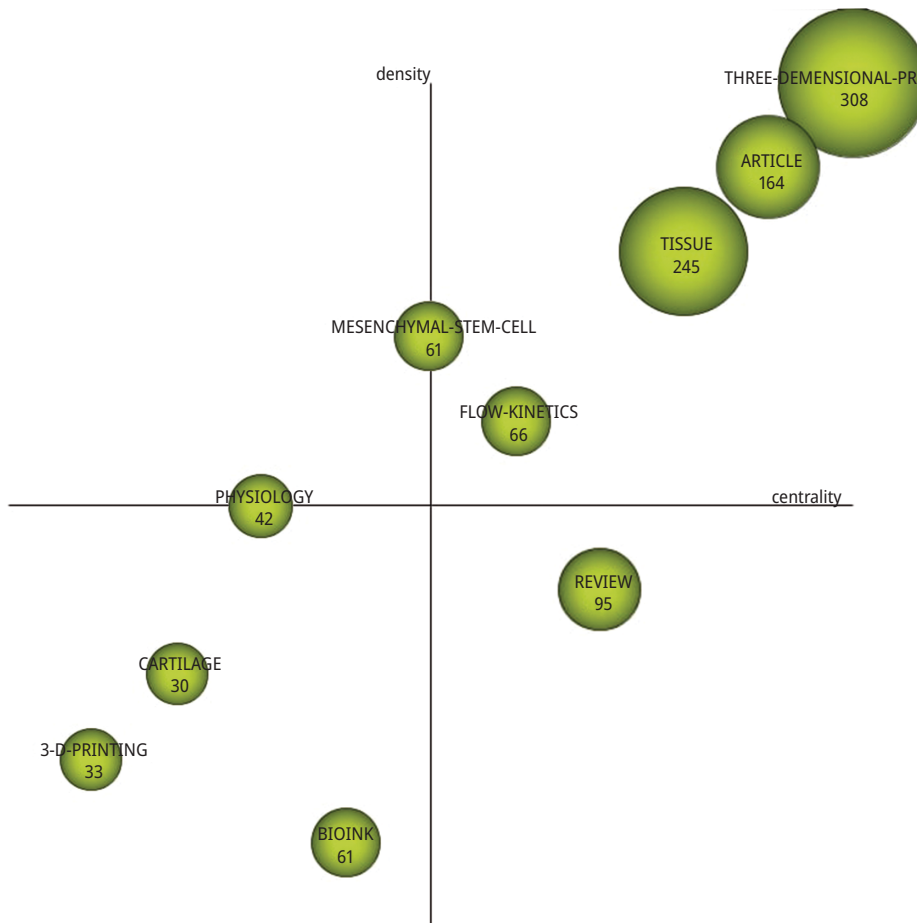


Fig. 2.10: Strategic diagram displaying the performance of the themes for the period 2012–2019.

evant to the present research study and around which a lot of development is going on. Review about 3D printing and its applications are available in the literature.

2.5.2 Second period (2020–March 2023)

This period is the latest one where the major themes are 3D-printer design and development for tissue engineering as depicted in Fig. 2.11. GEL is also one of the motor themes. Bone development is a highly developed theme. Biomechanics, stereo lithography, and cell proliferation are found to be emerging themes. ECM, which is the basic theme in this period of research helps cells to attach and communicate with

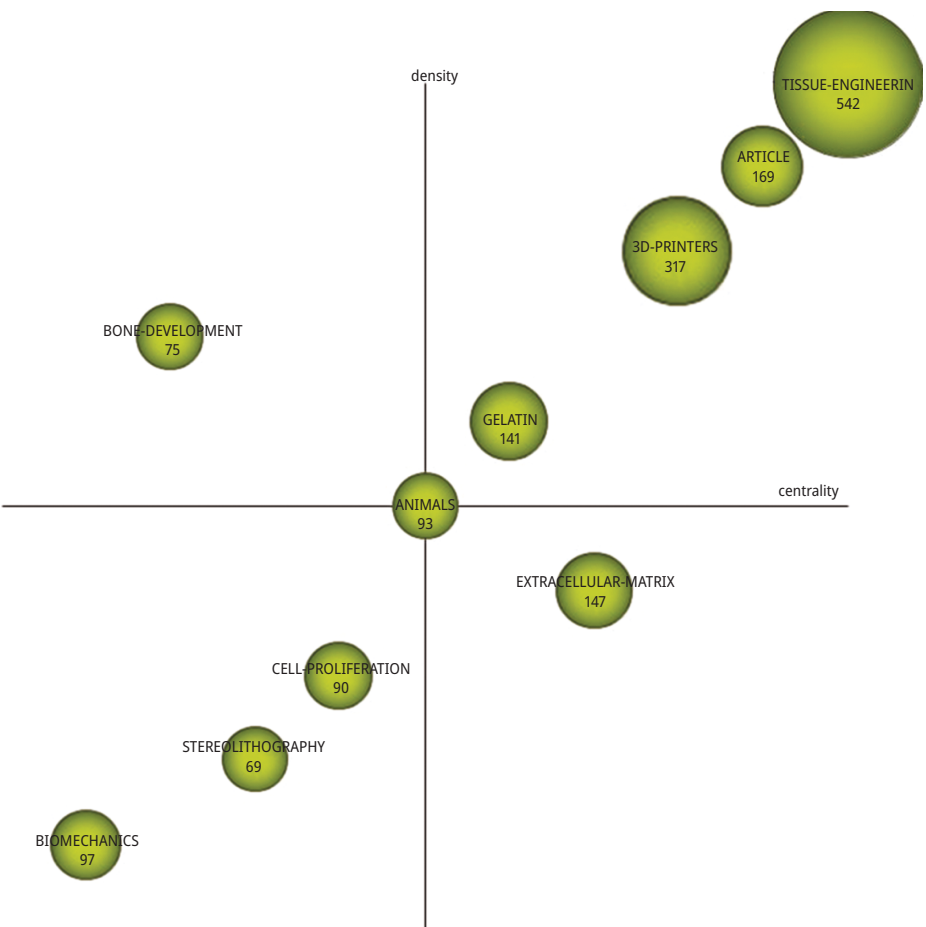


Fig. 2.11: Strategic diagram displaying the performance of the themes for the period 2020–2023.

other nearby cells. In addition to regulating cell development, cell movement, and cell repair, it plays an important role in maintaining tissue health.

Three-dimensional printing, which is a motor theme in the first period is strongly connected to bioprinting, tissue-engineering, procedures, animal research, and tissue scaffold as presented in Fig. 2.12. Using polymeric biomaterial [39] scaffolds, cells can attach to them and subsequently develop into tissues. A good number of research papers are available on 3D printing for tissue engineering using biomaterials and sustainable materials [40] for humans in priority journals.

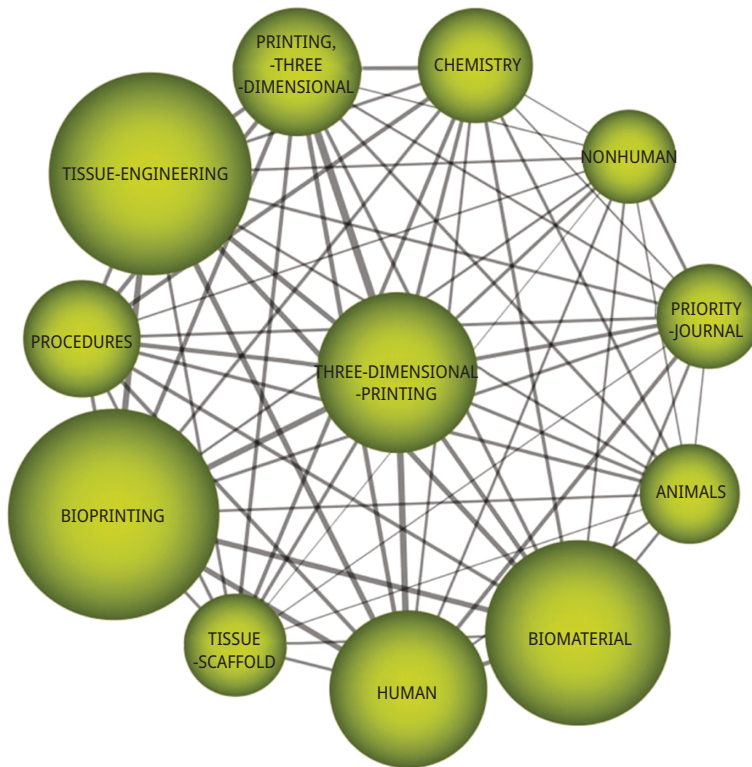


Fig. 2.12: Thematic network of three-dimensional-printing.

3D printers are well connected to cell engineering, biomechanics, 3D printing [40], scaffolds, and biocompatible materials as shown in Fig. 2.13. A lot of research work is going on in recent times to develop bioinks using cellulose nano fibrils and nanoparticles. Rheology, which is the study of the flow of soft solid, is also required for proper selection of bioink. Additionally, additive manufacturing [41–45] of biomaterials for surgical procedures is an emerging field. Bioprinting of hydrogels containing carbon materials is also being explored. As a diagnostic tool, cytology, which is also called

cytopathology, examines tissues and fluids from the body to determine the cause of the disease is also required for design and development of 3D printers. For 3D printers, knowledge of microanatomy or histology, which is the study of the microscopic anatomy of biological tissues, also plays an important role.

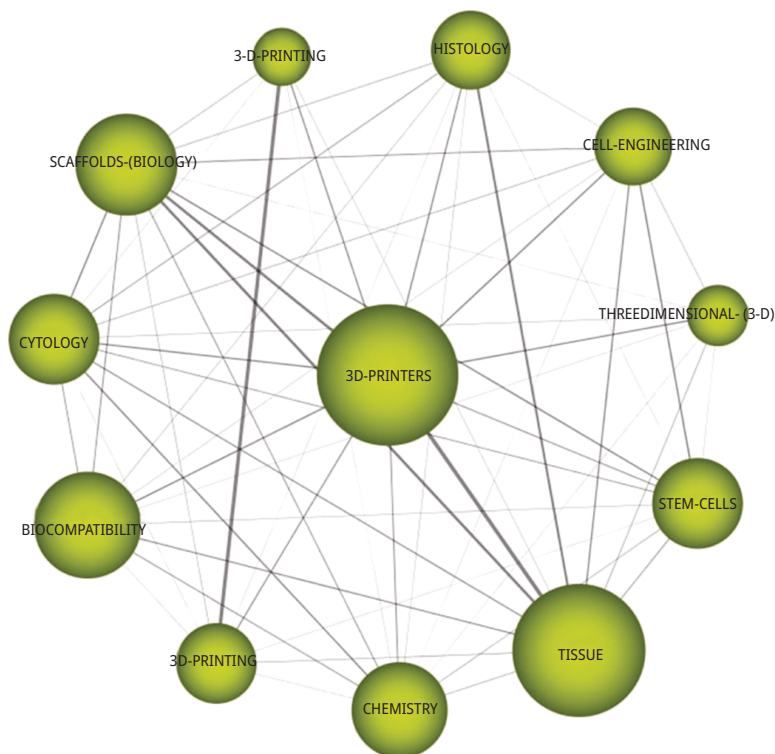


Fig. 2.13: Thematic network of 3D printers.

The thematic evolution of themes over the time period is displayed in Fig. 2.14. By analyzing the conceptual evolution of themes in each period, one can identify shared terms as well as how they change over time. The evolution process shows strong bonding between 3D printing, human, tissue, and printers. In the first period, 10 major themes were used, which are found to be strongly connected with 10 themes of the second period. In this context, it is essential to highlight that all the thematic areas include a fusion of motor themes – basic themes, highly developed and emerging themes have developed over time.

The overlay graph in Fig. 2.15 shows the stability of themes between the successive periods.

A total of 3,166 keywords were used in the first period, out of which 1,620 were deleted and 1,546 were carried forward. During the second period, 3,470 keywords

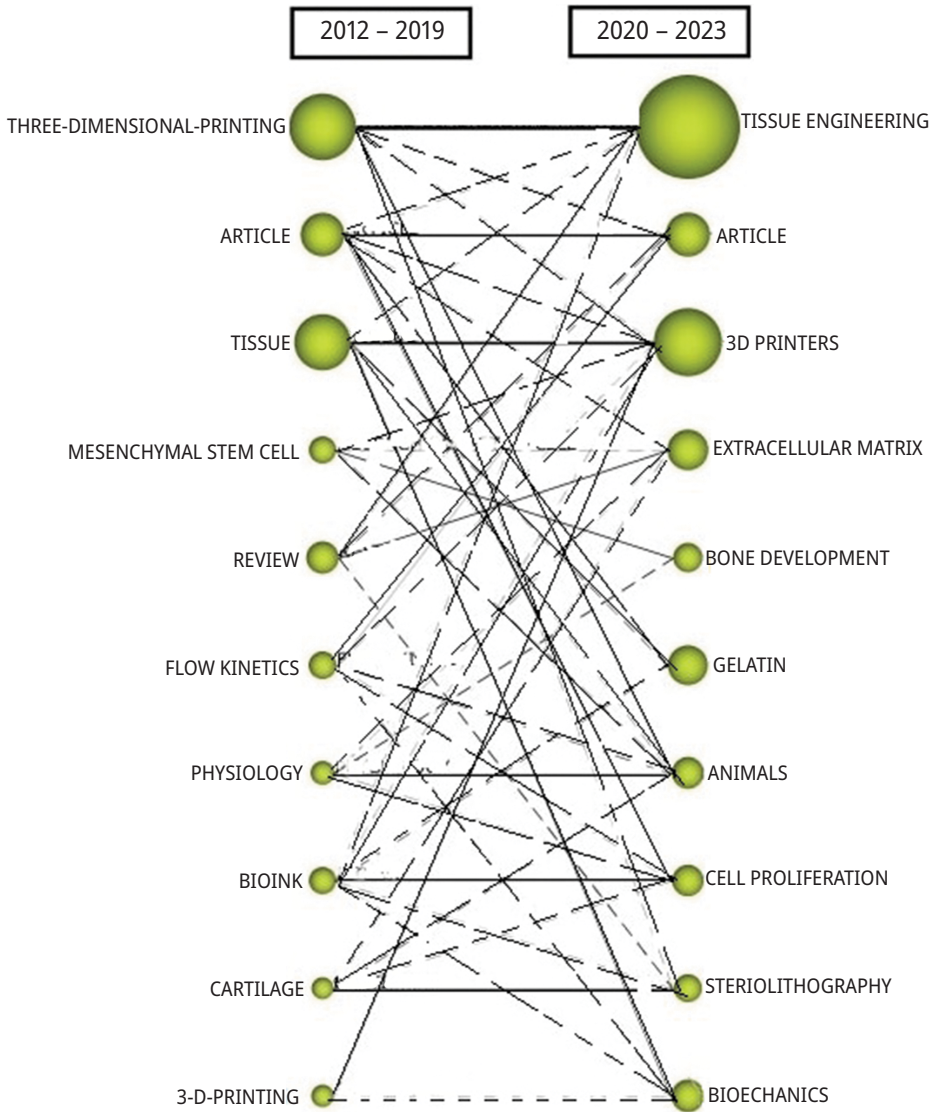


Fig. 2.14: Evolution map.

were added, bringing the total keyword count to 5,016. Within the circle, the total number of keywords is indicated, and the similarity index is 0.49. The inward arrow shows the emerging themes whereas the outward arrow shows the disappearing themes.

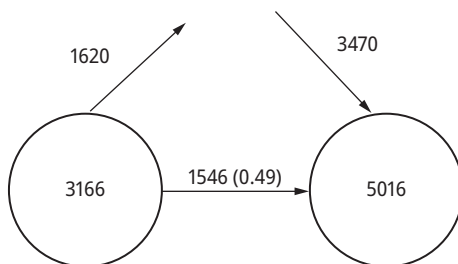


Fig. 2.15: Overlay graph.

2.6 Artificial intelligence in 3D bioprinting

The artificial intelligence (AI) algorithm can be used to enhance 3D bioprinting workflows – reducing the risk of errors, fine-tuning printing parameters, and expediting automated processes. It is widely accepted that AI can play an important role in the various phases of the 3D bioprinting process. The use of AI will also reduce failure rates in clinical trials by predicting outcomes of various applications of 3D printing. The machine learning branch of AI can identify the optimal parameters for the printing of tissues/organs for a particular patient by improving the quality of the results and detecting anomalies [46]. Through the implementation of machine learning in bioprinting and biofabrication, a dramatic transformation will be induced and bioprinting will become part of the digital industry and the information technology [47]. Machine learning is becoming increasingly popular and it is already being used to optimize 3D printing processes, predict material properties, identify manufacturing defects, and analyze dimensional accuracy [48]. AI approaches are used widely in smart manufacturing for biomedical industry [49, 50].

2.7 Conclusion

A bibliometric and thematic analysis of 3D bioprinting technology between 2012 and March 2023, with a focus on biomaterials and tissue engineering, is presented in the current study. Consequently, it analyzes and describes the development of research themes concerning biomaterials, bioinks, scaffolds, and tissue engineering, using literature and thematic analysis. By using this approach, scientists and researchers can identify new research that supports their interests. We identified significant countries, authors, and affiliations in the related field based on bibliometric analysis. A total of 1,053 publications have been analyzed and processed based on bibliometric volume. Over the last 11 years (2012–March 2023), the volume of literature related to 3D bioprinting technology, its applications, and matching themes has grown significantly. There have been a large number of publications and citations received in the

medical field, so this interest should continue to grow and support the existing healthcare system. A total of 3,923 researchers from 532 organizations published papers on 3D bioprinting between 2012 and 2023. The most productive authors are Xiaohong Wang, Yaoyao Zhang, and Xinwei Zhang, and the most cited authors are Michael Gelinsky, Sijia Li, and Tilman Ahlfeld. According to this analysis, the USA, China, Canada, and Korea are the most productive countries in terms of the highest numbers of published papers worldwide. In this emerging field, collaborative research among different countries is also presented. *Biomaterials*, *Biofabrication*, *Acta Biomaterialia*, and *Advanced Healthcare Materials* are the top leading journals with the maximum number of publications.

As a result of this study, the following themes have been identified as important to the scientific community in the future: tissue scaffolds, biomaterials, cell engineering, biocompatible materials, hydrogel, cell viability, regenerative medicine, smart manufacturing, and novel research approaches in fields related to 3D bioprinting.

This bibliometric and thematic analysis also suggests that there is a wide opportunity for research in designing and developing 3D bioprinters for the biofabrication of tissues using biomaterials. In this current study, academic literature and scholarly communication in the targeted field are analyzed qualitatively and quantitatively. Additionally, it offers valuable directions and findings to academic researchers working in the medical and healthcare sector. The role of AI in 3D bioprinting to determine the best printing parameters for creating biocompatible tissues for patients is also discussed.

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Mainak Saha

3 Additive manufacturing of compositionally complex alloys: trends, challenges, and future perspectives

Abstract: The recent decade has witnessed the evolution of a novel alloying paradigm based on using multiple elements to design compositionally complex alloys also known as high entropy alloys (HEAs). Conventional manufacturing of HEAs has a number of drawbacks, especially in terms of mechanical properties and design complexities. This has been addressed by additive manufacturing (AM), which has not only led to the fabrication of complex-shaped HEA components but has also enabled both ex situ and in situ control of alloy microstructures. In view of the recent developments in AM-based fabrication of HEAs, the present status and challenges in the avenue of AM of HEAs have been highlighted in the present chapter with special emphasis on the recent trends in the avenue of AM-based fabrication of HEAs from the viewpoints of (i) microstructure evolution and mechanical properties and (ii) alloy fabrication techniques.

Keywords: Additive manufacturing, compositionally complex alloys, microstructure-property correlation

3.1 Introduction

In recent times, there has been a huge number of investigations aimed at fabricating high-entropy alloys (HEAs) using additive manufacturing (AM) [1, 2]. This may be primarily attributed to the two factors: (i) microstructural optimization, and (ii) enhanced mechanical properties [2, 3]. The former is associated with defect density along with low cost (of production) whereas the latter is mainly a subset of the former factor [4–8]. In other words, the microstructure plays an indispensable role in terms of influencing the mechanical response of AM-based HEAs [4, 9]. It has been recently shown that AM-based HEAs possess a higher overall toughness (including yield strength and ductility) when compared to those of the bulk counterparts [10–13]. In addition, AM has provided a wide range of opportunities towards manufacturing HEA components with (i) high geometrical complexities and (ii) in situ tailoring of microstructures [14, 15]. The fabrication technique employed during AM highly influences the latter. For instance, the fine-grained microstructure evolved during rapid solidification has been reported to undergo hot isostatic pressing for further enhancement of mechanical properties through removal of synthesis

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defects and residual stresses in AM-based HEAs [16–20]. Moreover, the high cooling rates associated with AM-based techniques may be used to avoid undesired phase transformations and chemically homogenize the HEAs by restricting diffusion [21].

The thermal cycles associated with AM-based fabrication techniques lead to fine-grained microstructures with enhanced mechanical properties [19]. More specifically, the nonequilibrium nature of the AM-based fabrication techniques has also been reported to suppress intermetallic compound formation during solidification [19]. In a series of recent investigations, a number of techniques have been devised for controlling the microstructural features such as grain morphology, texture, residual stresses, and residual stresses (during solidification) [19, 22]. Two of the most common techniques to control the aforementioned features include (i) laser power and (ii) scan strategy [19]. From the viewpoint of microstructural features and mechanical properties, the recent advancements in the avenue of AM-based HEAs include the development of interstitial HEAs, core-shell structured HEAs, and HEA composites. From the viewpoint of HEA fabrication, development of non-beam AM techniques is a major breakthrough in the aforementioned avenue [19]. Considering the expanding interests of the alloy design community in the avenue of AM-based fabrication of HEAs (in the last few years), the present chapter begins with a brief discussion on the present status and challenges in the area of AM-based HEAs. This has been followed by a discussion on the recent trends in AM of HEAs from two different points of view, viz., (i) microstructural features and mechanical properties and (ii) alloy fabrication. Moreover, future perspectives in the avenue of AM of HEAs have also been highlighted.

3.2 Present status and challenges in the avenue of AM-based HEAs

The two most commonly used AM techniques for the fabrication of HEAs are direct laser deposition (DLD) and electron beam melting (EBM) [21]. On the other hand, the number of investigations on the selective laser manufacturing (SLM) of HEAs is rather limited [21]. In contrast to EBM and SLM techniques, which require pre-alloyed powders, DLD uses elemental powders to fabricate HEAs and also enables tailoring of HEA compositions [21]. Joseph et al. [23] have used the DLD technique to fabricate $\text{Al}_x\text{CoCrFeNi}$ HEA with different Al contents (x (mole fraction) = 0.3, 0.6, and 0.85). It was reported that a variation in Al content leads to three different types of microstructures, viz., FCC, FCC/BCC, and BCC. For instance, DLD-based $\text{Al}_{0.6}\text{CoCrFeNi}$ HEA shows a Widmanstätten microstructure at room temperature [23]. Comparing the DLD microstructure (of $\text{Al}_{0.6}\text{CoCrFeNi}$) with that of conventional arc-melted microstructure (Fig. 3.1) shows that there is no appreciable difference in terms of microstructural features in both FCC and BCC phases [23]. However, for the case of a dual-phase FCC + BCC microstructure, significant differences were observed between DLD and arc-melted microstructures [23]. This

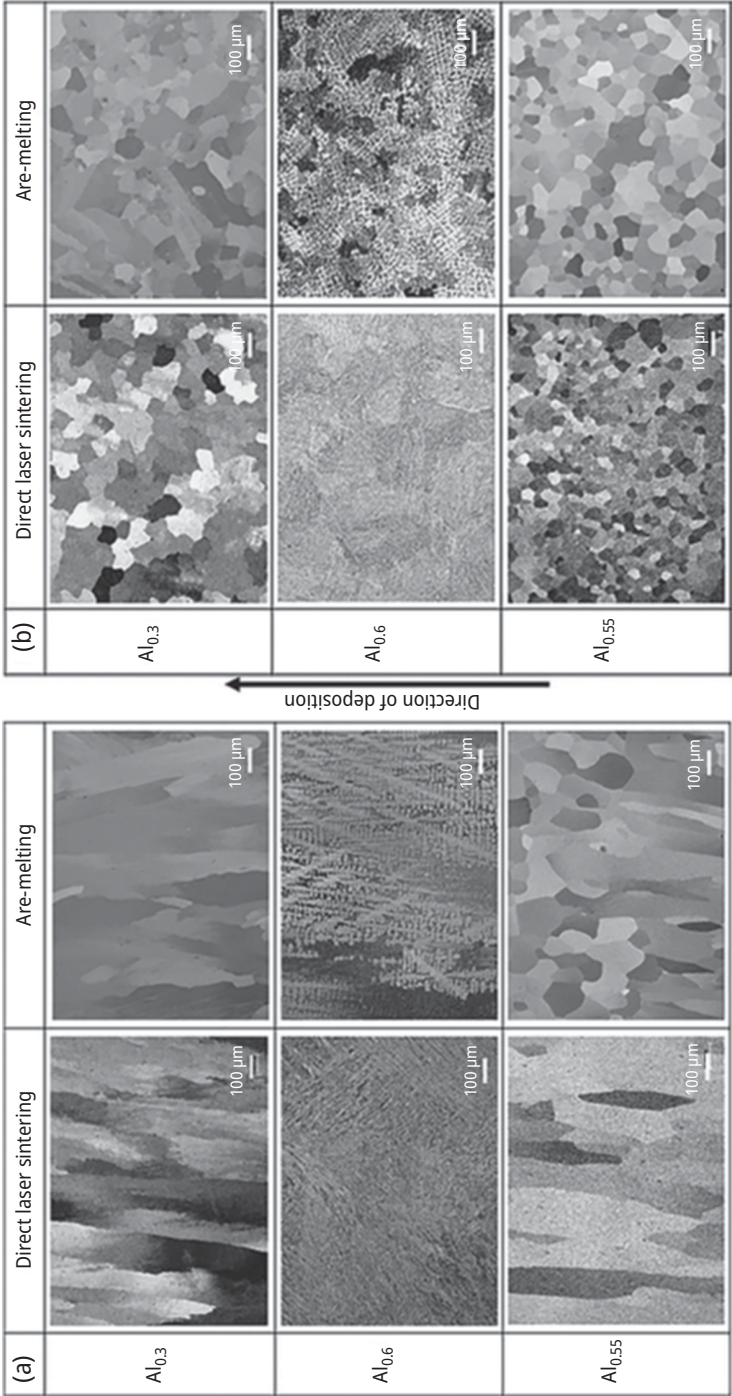


Fig. 3.1: DLD-based and arc-melted $\text{Al}_x\text{CoCrFeNi}$ HEA: (a) perpendicular to the solidification direction and (b) perpendicular to the cross-sectional area [23].

was attributed to the higher (i) cooling rates and (ii) temperature gradient in the melt pool for DLD as compared to that in conventional arc melting [23].

Sistla et al. [24] have investigated on how the Al:Ni ratio affects the microstructure evolution and phase stability in DLD-based $\text{Al}_x\text{FeCoCrNi}_{2-x}$. It was observed that a decrease in the Al:Ni ratio leads to a transition from BCC (lattice parameter = 0.288 nm) to FCC solid solution (lattice parameter = 0.357 nm) [24]. Ordering and spinodal decomposition in these alloys (during cooling) were attributed to lattice strain caused by Al [24]. In addition, as shown in Fig. 3.2, the microstructure is reported to undergo a transition from dendritic to equiaxed morphology [24]. Ocelik et al. [25] have investigated on the effect of laser processing parameters and that of Al on the phase stability of AlCoCrFeNi equiatomic HEA. It was reported that high cooling rates lead to a high probability towards formation of BCC phase [25]. Moreover, it was also highlighted that the efficiency of DLD technique depends on a number of process parameters, which include rate of powder intake, powder melting temperature, laser scan speed, and laser power density [25]. Dobbstein et al. [26] have used the DLD technique to fabricate MoNbTaW refractory HEAs (RHEAs) using premixed powders. Based on this work, it was highlighted that in situ alloying during DLD may be used to fabricate HEAs [26]. This study demonstrated that it is possible to control the process parameters (involved in fabrication) by fine-tuning the HEA composition [26]. In the context of RHEA fabrication, a point worth noting is that all refractory metals are highly sensitive to oxidation [26].

EBM has been reported to ensure chemical homogeneity of the fabricated HEAs by using pre-alloyed HEA powders [21]. This is in contrast to DLD, which uses elemental powders for fabricating HEAs [21]. In the context of EBM-based AlCoCrFeNi HEAs, Fujieda et al. [27] have reported that the synthesized alloy has a dual-phase FCC + BCC microstructure (evolved during preheating) whereas the raw powders had a single-phase BCC structure (Fig. 3.3(a)). BCC grains in EBM-based HEA were oriented along the build direction (BD) (Fig. 3.3(b)) [27]. Moreover, the EBM-based HEA was reported to exhibit a fine-grained microstructure in contrast to the specimen prepared by casting (Fig. 3.3(b)) [27]. This was attributed to the high cooling rates followed during EBM [27]. Both Fe and Co were observed to segregate at grain boundaries (GBs) in EBM as well as cast specimens [27]. Besides, the bottom part of the fabricated HEA component showed a higher fraction of equiaxed FCC grains compared to the top portion of the component [27]. This was attributed to the longer preheating process, which led to the transition from BCC to FCC crystal structure [27]. In the context of AlCoCrFeNi HEA, Shiratori et al. [29] have reported a microstructure comprising nano-lamellae of BCC and B2 phases. The FCC phases were observed along the GBs of the BCC/B2 phases [29]. This was attributed to the preheating followed during EBM [29]. In addition, BCC/B2 grains were elongated along BD on both the top and bottom parts of EBM-based sample [29].

A similarity was observed in terms of the microstructure of the top portion of EBM-based specimen and cast specimens [29]. On the other hand, microstructural coarsening was observed in the bottom portion where the volume fraction of FCC grains was higher than that of the BCC grains. Fujieda et al. [30] have fabricated CoCr-

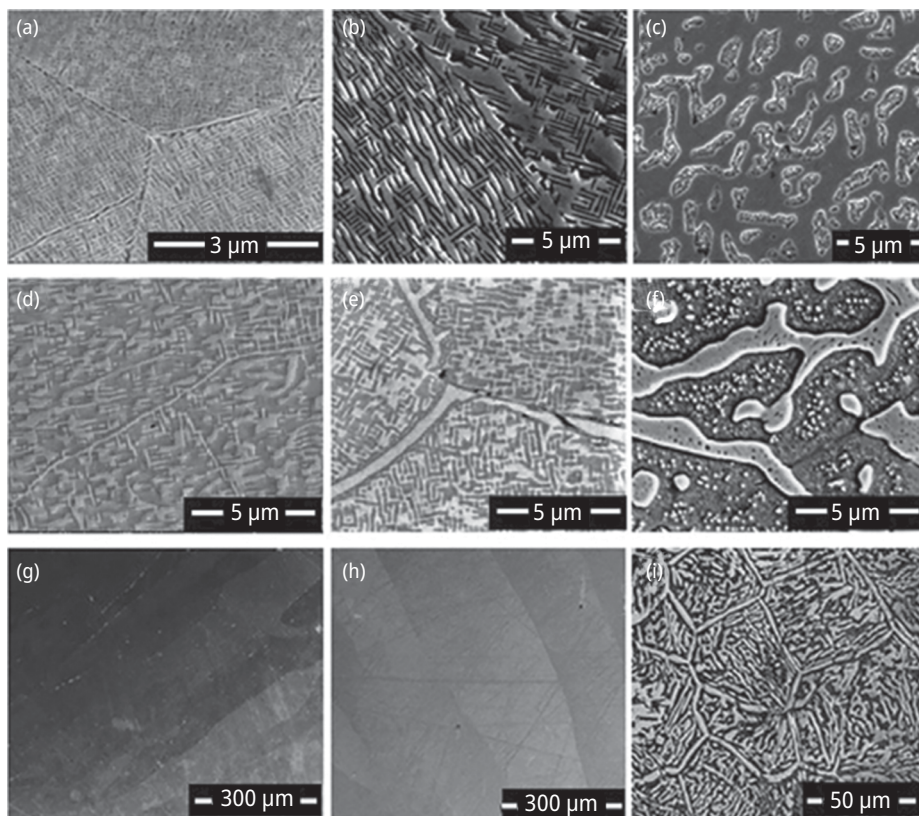


Fig. 3.2: DLD-based AlCoCrFeNi HEA: **(a)** equiaxed grains with modulated precipitates; **(b)** coarse modulated structures in the as-quenched condition; **(c)** Fe–Cr-rich precipitates in the B2 (ordered BCC) matrix in annealed condition; **(d)** Fe–Cr-rich precipitates in Ni–Al-rich matrix deposited in pulsed mode; **(e)** grain boundaries (GBs) in coarse microstructure in as-quenched condition; **(f)** coarse Fe–Cr-rich precipitates formed due to a high rate of diffusion of constituent elements (Al, Co, Cr, Fe, and Ni) during annealing. DLD-based $\text{Al}_{0.3}\text{CoCrFeNi}_{1.7}$ HEA: **(g)** columnar grain structure in as-fabricated condition; **(h)** columnar grain structure after quenching; and **(i)** equiaxed grains with coarse Al–Ni-rich precipitates (coarsened due to annealing) [24].

FeNiTi HEA using selective EBM (SEBM) technique. In the case of SEBM-based specimen, Ni_3Ti precipitates (with basket weave morphology) were observed in the FCC matrix [30]. On the other hand, both Ni_3Ti and $(\text{Cr}_{11}\text{Fe}_{13}\text{Ni}_4)\text{Mo}_3$ intermetallic phases were detected in the cast HEA (Fig. 3.4(a)) [30]. Clustering of both Ni and Ti elements was observed in the SEBM-based specimens, in as-fabricated condition [30]. In addition, it was reported that Ni_3Ti precipitates completely disappear after solution treatment (Fig. 3.4(b–d)). It is also noteworthy to mention that fine ordered phases (enriched with Ni and Ti and with ~ 40 nm size) were formed in the FCC matrix as shown in Fig. 3.4(b–d) [30]. The formation of these phases was ascribed to the spino-

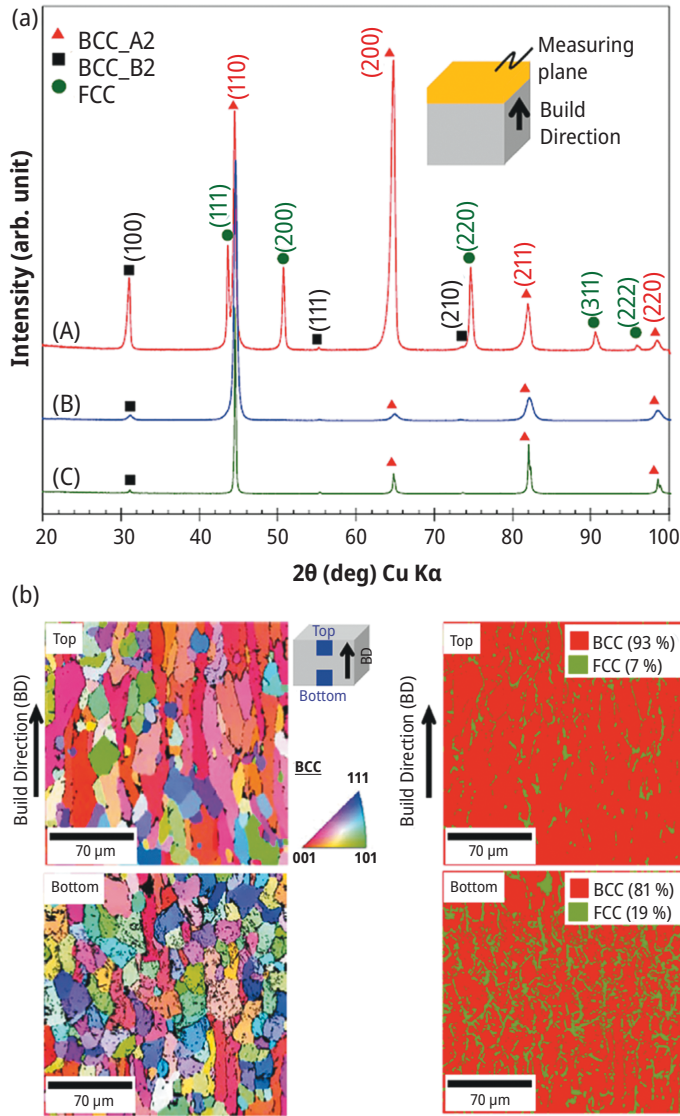


Fig. 3.3: AlCoCrFeNi HEA: (a) X-ray diffraction (XRD) patterns of the EBM-based (red), as-cast specimen (blue) and the gas-atomized powders (green) and (b) electron backscatter diffraction (EBSD)-based inverse pole figure (IPF) maps (left) and phase distribution maps (right) of the top and bottom portions EBM-based specimens [28].

dal decomposition [30]. Brif et al. [32] have fabricated equiatomic FCC-structured FeCoCrNi HEA through SLM of pre-alloyed powders. Based on this work, it was demonstrated that post-heat treatment is necessary for chemical homogenization of SLM-based HEA specimens [32].

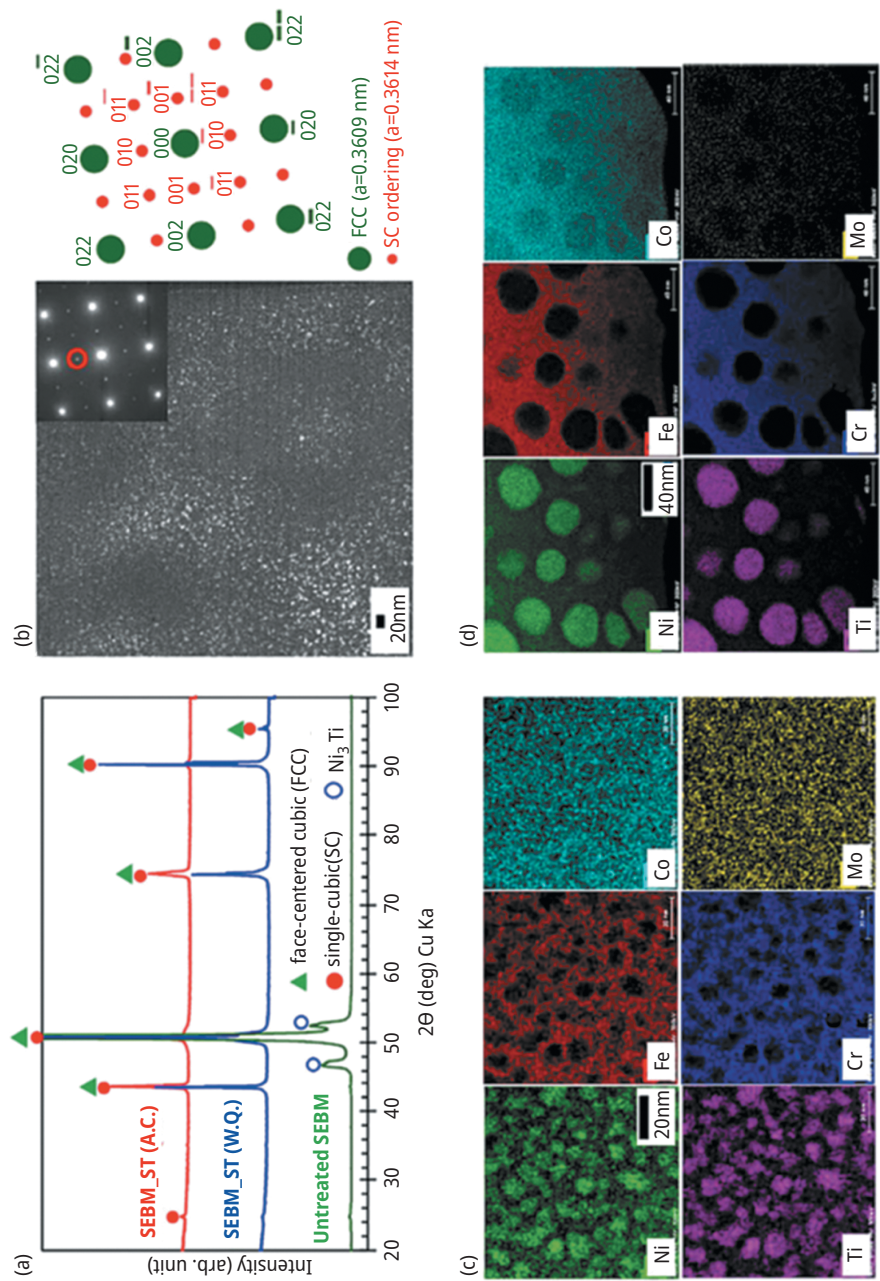


Fig. 3.4: SEBM-based CoCrFeNiTi HEA: **(a)** XRD patterns in the fabricated and solutionized conditions, **(b)** transmission electron microscopy (TEM)-dark-field (DF) image and corresponding selected area diffraction pattern (SADP) after solutionizing (inset), **(c)** (scanning) transmission electron microscope

3.3 Trends in AM-based fabrication of HEAs

3.3.1 From the viewpoint of microstructural features and mechanical properties

3.3.1.1 Design of interstitial HEAs

Zhu et al. [33] have reported the feasibility of fabricating dense C-added $\text{Fe}_{49.5}\text{Mn}_{30}\text{Co}_{10}\text{Cr}_{10}\text{C}_{0.5}$ interstitial HEAs using SLM technique. It was highlighted that the overall toughness of SLM-based specimens were significantly higher than those of the conventionally cast specimens with coarse-grained microstructures [33]. A number of deformation features such as planar slip bands and deformation twins formed during the early stages of deformation in SLMed HEA [33]. However, with increase in the extent of deformation (to $\sim 12\%$), intersection of slip bands with profuse stacking faults (SFs) was observed [33]. These were reported to promote strain-hardening leading to an overall enhancement in both strength and ductility of SLMed HEA [33].

Park et al. [34] have reported that addition of ~ 0.2 wt% C enhances the mechanical properties of SLMed CoCrFeMnNi equiatomic HEA. Two laser scanning speeds were used, viz., 200 and 600 mm/s [34]. Enhancement in mechanical properties was attributed to a number of factors, viz., solid solution strengthening, formation of dislocation pileups, and grain refinement [34]. Addition of C was interestingly observed to promote the formation of Cr_{23}C_6 , MnO, and MnS in the form of nanoprecipitates [34]. In the case of 200 mm/s, it was observed that slow speed of laser scanning leads to Mn and Ni segregation at cellular networks [34]. Segregation of these elements was reported to induce plastic strains at the interface, leading to the dislocation pileups in the interfacial region [34]. The back-stresses produced due to this pileup contribute to the enhanced strain hardening properties of $(\text{CoCrFeMnNi})_{99}\text{C}_1$ HEA [34]. In the context of SLM-based fine-grained $\text{FeCoCrNiC}_{0.05}$ with FCC microstructure comprising cellular and columnar subgrains, mechanical properties of the alloy are largely dependent on the laser power and travelling speed. Precipitation of nano M_{23}C_6 carbides was obtained at GBs and dislocation networks. In addition to a number of defects such as nanotwins, the microstructure also showed the presence of SFs and sessile Lomer lock [35]. The overall elongation of C-doped SLM-based samples was reported to be significantly lower compared to those of non C-containing SLMed specimens and C-containing cast specimens [35]. Song et al. [36] have doped nitrogen (N) in SLM-based CoCrFeNi HEA. A hierarchical microstructure comprising low-angle (or subgrain) boundaries and dislocation net-

Fig. 3.4 (continued)

(STEM)-energy-dispersive X-ray spectroscopy ((S)TEM-EDS) elemental maps with elemental mappings for specimens water-quenched after solutionizing, and **(d)** STEM-EDS-based elemental maps after normalizing (in post solution-treated condition) [31].

works was obtained [36]. Besides, N was reported to induce strengthening through grain size refinement [36].

3.3.1.2 Core-shell structure

In the context of AM-based HEA, Zhang et al. [37] have used liquid-phase separation technique to demonstrate the core-shell formation during solidification (of the alloy). It was reported that the microstructure undergoes liquid-phase decomposition for transition from dendritic to a core-shell structure. This decomposition was attributed to the addition of 1 wt% Y_2O_3 in the form of nanoparticles in a laser-cladded $AlCoCrCuFeNiSi_{0.5}$ HEA [37]. However, no such decomposition was observed in the absence of Y_2O_3 . Y_2O_3 nanoparticles were reported to be the catalyst for the above decomposition [37]. The formation of Cu-rich FCC phase in addition to the existing FCC + BCC dual-phase microstructure was observed in the presence of Y_2O_3 nanoparticles [37]. Cu-rich FCC phase was observed to be present only in the core. Moreover, a uniform distribution of core-shell structures was reported in the BCC matrix phase [37]. The formation of core-shell structure was also reported in laser-cladded $CoCrFeNiAl_xCu_{0.7}Si_{0.1}B_y$ ($x = 0.3$ and 2.3 , $0.3 \leq y \leq 0.6$) HEA coatings [38]. However, till date, there is no report on the mechanical properties of these coatings.

3.3.1.3 HEA-based composites

At present, HEA-based composites (HEACs) comprising borides, nitrides, carbides, and oxides (added both ex situ and in situ during AM-based fabrication) have been introduced for the purpose of tailoring the microstructure of AM-based HEAs [39, 40]. The first report in this avenue was obtained from Li et al. [40] where DLD technique was used to deposit three compositions, viz., $FeCoCrAlCu$, $97.5(FeCoCrAlCu)-2.5(YPSZ)$ (YPSZ: Ytria partially stabilized zirconia), and $90.5(FeCoCrAlCu)-2.5(YPSZ)-7(SiB_2)$ (wt%) on TC17 Ti alloy. Moreover, formation of $AlCu_2Zr$ ultra-nanocrystals (UNs) was observed and ascribed to the highly positive magnitude of mixing enthalpies between Cu and other elements in $FeCoCrAlCu$ [40].

$CoCrFeMnNi-5$ wt% TiC composite was reported to possess an ultimate tensile strength (UTS) of ~ 723 MPa with an overall ductility of $\sim 32\%$ [39]. On the other hand, $CoCrFeMnNi-5$ wt% WC composite was reported to show comparatively higher UTS (~ 800 MPa) with a slightly higher elongation ($\sim 37\%$) [39]. Enhancement in mechanical properties was attributed to the hindered propagation of slip bands due to the presence of TiC (in the form of second phase for TiC-reinforced composite) or $Cr_{23}C_6$ precipitate [39]. Similarly, Li et al. [41] have reported on the fabrication of $CoCrFeMnNi-TiN$ HEA using SLM technique. Pre-alloyed powders of $CoCrFeMnNi$ (fabricated using gas atomization) and nanoparticles of TiN were used as the starting materials for this

fabrication. Strengthening of the alloy was attributed to pinning caused by the presence of uniformly dispersed TiN nanoparticles. UTS and overall elongation of the alloy was reported to be ~ 1036 MPa and 12%, respectively [41]. In addition, Li et al. [41] have fabricated $\text{Fe}_{43.7}\text{Co}_{7.3}\text{Cr}_{14.7}\text{Mo}_{12.6}\text{C}_{15.5}\text{B}_{4.3}\text{Y}_{1.9}$ metallic glass reinforced CoCrFeMnNi HEAC using SLM. These composites were reported to possess UTS in the range of ~ 916 – $1,517$ MPa [41]. UTS of these composites was reported to be influenced by the volume fraction of metallic glass [41]. Jiang et al. [42] and Chen et al. [43] have fabricated AlCoCrFeNiTi– CeO_2 and AlCoCrFeNiTi–TiC coatings respectively using laser cladding. Self-generation of TiC particles was reported with an increase in the fraction of B and C (from 2 to 4 wt%) [43]. Moreover, B and C were reported to cause a crystal structure transition (of coatings) from FCC to BCC [38, 43]. It was further reported that the mechanical properties of laser-cladded AlCoCrFeNiTi–1 wt% CeO_2 were enhanced in comparison with those of AlCoCrFeNiTi HEA [43].

3.3.2 From the viewpoint of HEA fabrication

3.3.2.1 Non-beam AM techniques

One of the most recent developments in the field of AM is the development of powder-based liquid ink AM techniques. The most common technique using this approach is 3D ink extrusion which involves formation of a green structure through room temperature printing of an ink-containing mixture of precursor powders. This is followed by a number of steps for transformation of the green component into a sintered one [44]. Recently, Kenel et al. [44] have used this technique to fabricate microlattices of CoCrFeNi quaternary HEA. This technique has been reported to overcome segregation-based inhomogeneities, thereby reducing the residual stresses in the printed component [44]. In the work of Kenel et al. [44], the printable ink for 3D ink extrusion AM technique was developed by blending a number of oxide nanopowders, namely Fe_2O_3 , NiO, Co_3O_4 , and Cr_2O_3 with a polymeric mixture [44]. This was followed by the extrusion of the ink into 200 nm microlattices [44]. These microlattices were subsequently made to undergo co-reduction, interdiffusion and sintering in H_2 atmosphere [44]. The CoCrFeNi HEA was prepared by reduction and metal inter-diffusion of the sintered product [44]. This alloy was reported to show excellent sub-zero temperature mechanical properties (including UTS ~ 864 MPa and elongation $\sim 37.6\%$ at 137 K) [44]. Surjadi et al. [45] have fabricated 3D polymeric coatings composed of core–shell structured microlattices of equiatomic CoCrFeMnNi (with high specific compressive strength of $\sim 0.018\text{MPa/kg m}^3$) using stereolithography (for the fabrication of polymeric scaffold) and RF magnetron sputtering techniques (for coating CoCrFeMnNi HEA thin film onto the scaffold).

3.4 AM of HEAs: future perspectives

In addition to powder-bed based AM techniques, powder-flow based AM methods involve a series of thermomechanical and nonequilibrium processing techniques [21]. These involve cyclic heating and cooling of the fabricated specimens [1]. This sets AM-based techniques apart from conventional fabrication techniques. In the context of AM for HEAs, the present state of research is focused mainly on utilizing HEA powders produced by gas atomization technique [2]. As highlighted by Li [21], not all HEAs can be fabricated using AM. This necessitates extensive investigations on the (i) optimization of different process parameters associated with different AM-based nonequilibrium processes and (ii) composition and microstructure of HEAs. For instance, a number of parameters such as laser velocity, laser power, laser absorptivity, fluidity (of the metal), and powder melting temperature need to be considered during SLM of HEAs [3, 9]. In addition, the fracture toughness of the HEAs and the ability to overcome high residual stresses associated with high thermal gradients (during AM-based fabrication techniques) must be considered for the design of AM-based HEAs [21].

The other challenge to be overcome is to establish a systematic structure-property correlation in AM-based HEAs [21]. For instance, there is limited information on how laser parameters such as laser power and density affect the homogeneity of the melt pool in terms of its composition in HEAs [21]. In addition, the influence of interstitial elements such as B, N, and C and contaminants (e.g., oxygen) on the evolution of phases and mechanical response of AM-based HEAs is not completely clear [21]. Besides, not much is known about the solidification process (during AM) and its associated influence on the residual stress [23]. In the context of mechanical properties, creep deformation behavior and fatigue response of AM-based HEAs are the areas where limited information exists [19, 27]. Besides, the poor surface quality of AM-based HEAs necessitates extensive surface machining. Altogether, these are the major avenues that show enormous potential for future experimental and theoretical investigations [46]. In this context, it is important to highlight that laser shock peening (LSP) has already been reported to show tremendous potential towards improving mechanical properties (through the reduction of porosities) [19]. However, extensive microstructural investigations are required to understand the compatibility of different HEA systems with LSP before commercializing the process [19]. Such investigations are also necessary to understand the mechanism(s) and sequence of precipitation hardening in age-hardenable AM-based HEA systems [19].

From a broader viewpoint, AM-based fabrication techniques for HEAs are currently based on a trial-and-error principle, which is still at its very early stage, highly time-consuming, and also costly [47]. Besides, there is limited interaction volume between the source of energy and powder particles associated with the characterization of melt pool during AM [48]. This may be attributed to very high heating and cooling rates associated with AM-based fabrication methods [48]. Hence, there is very limited information on the cooling characteristics at different regions of the melt pool during AM-based fabrication techniques [24]. Moreover, owing to the nonequilibrium nature of AM-based

fabrication techniques, a number of process and material parameters influence the fabrication process [23]. Understanding these parameters experimentally is highly challenging. In order to overcome this issue, experimental observations need to be coupled with appropriate computation-based modeling approach. Currently, hybrid AM techniques are being developed with high manufacturing capacity at a low operational cost. Nevertheless, such developments may be expected to render AM-based fabrication as a suitable option for large-scale economic manufacturing of HEAs.

3.5 Conclusions

The chapter presents an overview of the current state of research in the avenue of AM of HEAs with a special focus on (i) structure-property correlation, and (ii) fabrication techniques. At present, fabrication of fabricating complex geometric HEAs using conventional fabrication techniques needs further investigations (more particularly, microstructure-based investigations). In order to utilize the tremendous potential offered by AM-based fabrication of HEAs, not only novel HEAs need to be developed but also new fabrication techniques (such as 3D ink extrusion technique, as discussed in Section 3.2.1) for fabricating structurally homogeneous HEAs at low cost need to be designed. Besides, there is a huge requirement of coupling the experimental observations with appropriate computation-based modeling approaches. It is also worth mentioning that novel compositions (of the inks) and sintering mechanisms during 3D ink extrusion need to be further investigated.

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4 Adoptability of additive manufacturing process: design perceptive

Abstract: The application of additive manufacturing (AM) has expanded to previously unseen areas in business and academia. The ability to fabricate complex structures using AM includes everything from a part's overall geometry to the topology of its internal structural design. Designing for AM presents a challenge along with its freedom of fabrication. The challenges include modeling and optimizing intricate geometries, integrating AM design knowledge into the product, and increasing the usability of design for AM tools. To successfully shape the future AM environment, reflecting on the most recent advancements in structural optimization and design for AM (DfAM) is essential. The recent development of three-dimensional (3D) printing allows researchers to produce complex structures, permitting unique production processes show standard synthetic engineering approaches in terms of resolution and control precision. Machine learning (ML) is a growing technology that focuses on enabling software to improve the process. ML approaches enhance the effectiveness of AM design, process, and the final product. This article provides a detailed review of the insights into DfAM concepts in AM. In the end, the most up-to-date applications of ML concepts in integrating DfAM are reviewed.

Keywords: Additive manufacturing, DfAM, machine learning, topology optimization

4.1 Introduction

The term “additive manufacturing” (AM), commonly referred to as “3D printing” or “rapid prototyping,” refers to layer-upon-layer fabrication technologies that are controlled by CAD models. In the past, rapid prototyping was the primary application for AM [1–3]. The rapid prototyping capability of AM is being utilized to fabricate complex 3D objects in polymer science and technology, biomedical, nuclear, space fields, and so on.

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Based on the input material, 3D printing is primarily considered a solid, liquid, or power-based technique. Fused deposition modeling (FDM) is utilized to create a solid-based pattern, selective laser melting (SLM) and selective laser sintering (SLS) are employed to develop power-based patterns, and direct ink writing (DIW), digital light processing (DLP), and stereolithography (SLA) technologies build up the liquid-based patterns. A schematic of FDM, SLS, and SLA is shown in Fig. 4.1.

AM is widely used in many fields now. Net-shaped products like medical equipment and structural aircraft components are produced using the AM method [4–7]. This has made it a disruptive technology in the manufacturing industry, forcing designers to rethink the traditional product development process to utilize the benefits and potential of AM fully. AM may become quite expensive compared to most other conventional technology. After all, let us not forget that AM is a costly manufacturing technology, mainly due to the slow additive building process, but this is not always the case; AM can be cost-effective when producing geometrically complex parts, which are almost impossible to manufacture using conventional subtraction techniques. AM is mainly responsible for successfully implementing the present industrial revolution, known as Industry 4.0, which affects how we design and construct.

Compared to traditional manufacturing methods, AM has three potential benefits: producing custom designs without increasing costs, creating intricate structures with integrated functionality, and making lighter structures. All of these benefits place an intense demand on the design process, which has given rise to the field of design process in AM. The design for manufacture and assembly (DfMA) design process strongly emphasizes assembly productivity and manufacturing simplicity. A model can be produced and assembled more efficiently, rapidly, safely, and at less cost by optimizing its design. AM has substantially diverged from the DfMA regulations and now needs its own set of rules, known as design for AM (DfAM). “DfAM” refers to the technique and ability to design for AM [8, 9]. With this additive design process, engineers may build production parts with complicated designs, while utilizing less weight and material, than they otherwise would with traditional manufacturing [10].

DfAM provides optimized strategies that allow reducing the mass of a part while maintaining its structural integrity, thus increasing the strength-to-weight ratio. DfAM or designing for add manufacturing, is when designers seek to design a product that entirely takes advantage of the unique capabilities of AM. Therefore, DfAM is simply a DfM category dealing specifically with parts manufacturing through AM. Jiang et al. [11] conducted a thorough study on using AM to produce essential and optional spare parts, and increase product customization. This calls for enhanced structural performance and sensible design methods (DfAM).

The DfAM process is classified into three categories: system design, parts design, and process design. These categories should be seen as sequential steps with create goals for each step. The three primary standards specified for applying DfMA to the final products are as follows [12]:

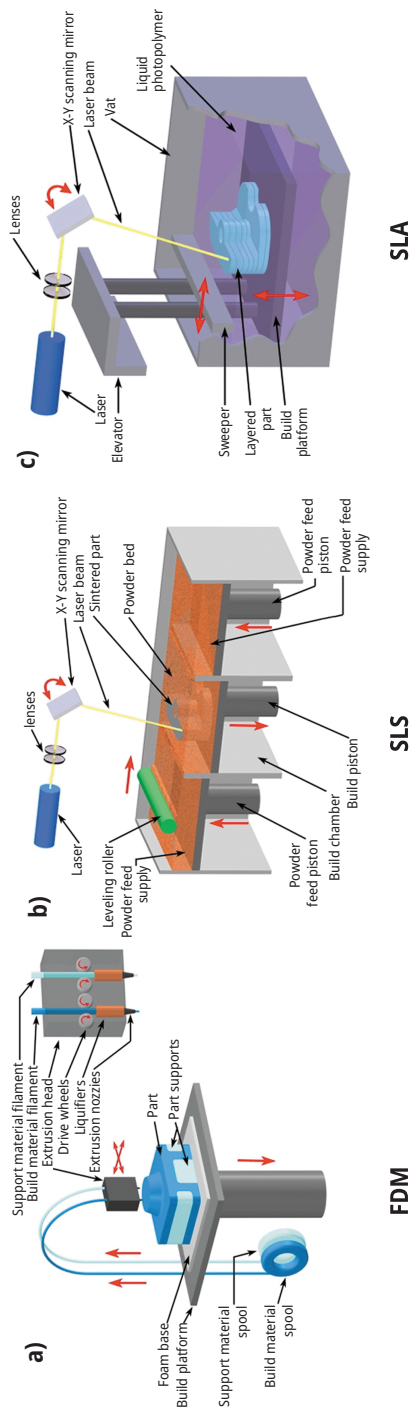


Fig. 4.1: General 3D printing process schematic: (a) FDM (solid-based), (b) SLS (liquid-based), and (c) SLA (power-based) (sources: <https://www.custompartnet.com>).

- (1) To cut costs associated with production and assembly and improve the product quality, the design team simplified the product's structure.
- (2) A tool was created to help with manufacturing and assembly-related quantity difficulties.
- (3) A tool was also developed for reducing costs and for contract negotiations with suppliers.

Over the past few decades, it has proven effective in several research fields, including searching for new materials and exploring different materials properties. The framework for design and structural optimization for AM is shown in Fig. 4.2, which links essential intrinsic and extrinsic DfAM characteristics. As a result, while building for AM, an internal aspect matters most, while extrinsic factors are what designers and structural optimists are now researching.

Understanding DfAM is essential if 3D printing is used in a manufacturing process. Therefore, optimizing or designing for AM contributes to and leads to success by adding more value and reducing the costs of the produced parts. This chapter covers the fundamentals of DfMA and the intermediate and advanced concepts as also a review of how AM can be more adaptable for product making, based on a design perceptive. Following this, the applications of machine learning (ML) in integrating DfAM are reviewed.

4.2 Design for additive manufacturing (DfAM)

4.2.1 Design by topologic optimization

Topology optimization (TO), an extensively used simulation-driven design technology in product design, can aid manufacturers. TO is a computational modeling approach that aims to create an effective material distribution to address a specific problem, based on load situations, material characteristics, and boundary conditions [14, 15]. TO generally offers an experience to offer a workable solution, when faced with a complex product, packaged in a small space that must handle several loads. TO provides geometries that can be quickly developed into full products, enabling rapid design exploration, and increasing the productivity. This way, physics is used to increase human creativity [16].

The majority of computer-assisted engineering (CAE) techniques is inadequate with CAD representation of AM parts and pose difficulty for the simulation-based design of AM parts. TO techniques are widely used to create intricate yet lightweight structures that set many AM parts apart. Incorporating TO techniques in direct AM is significant in achieving rapid optimization design and manufacturing in industries. The main aspects to take full advantage of TO to reach high DfAM are designing high-performance multiscale structures and integrating AM design limitations into TO [9, 17].

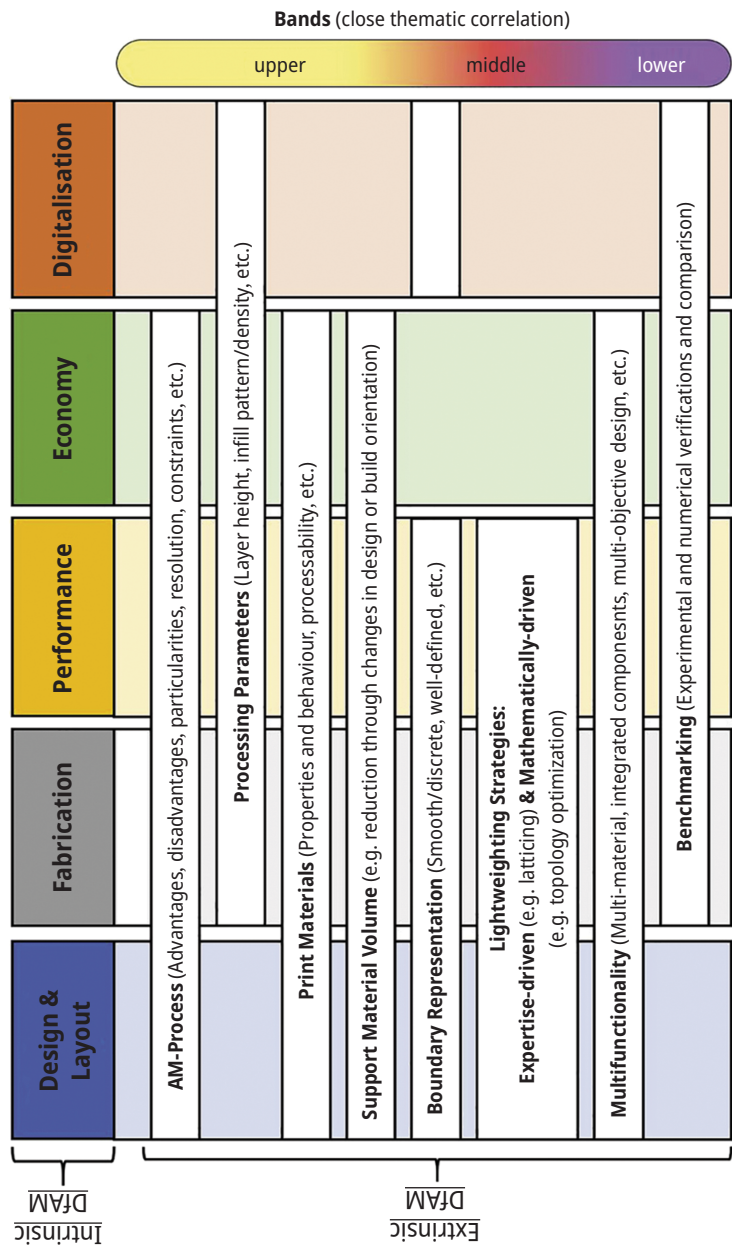


Fig. 4.2: DfAM framework-composed design and structural optimization [13].

4.2.2 Optimization design of multiscale structures

Lattice structures and porous microstructures have drawn increasing attention from researchers as lightweight and multifunctional structures [18]. The optimization in designing multiscale/hierarchical lattice structures has recently gained much attention from scholars as a significant research region in integrating TO and AM. Recent research indicates that a nonuniform hierarchical structure can perform considerably better than uniform lattice microstructures [19].

Density-based method, concurrent optimization, and large-scale strut-sizing optimization, based on homogenization, are the growing research areas in integrating AM and TO. The production of multiscale/hierarchical lattice structures by conventional methods (machining, weaving, welding, etc.) involves complex procedures and long labor hours [20–26]. Complex and hierarchical lattice structures can be produced rapidly and precisely using AM techniques like SLM [27]. Complex lattice unit cells were created on a mesoscale or microscale to produce a specified gradient of elastic characteristics. However, it must be noted that any production method has its limitations. AM is no different. Recent studies have focused, in particular, on the built-up constraints of lattice structures made using various AM methods.

Investigations have been conducted on 316L stainless steel gyroid lattice structures, produced by SLM [28]. Three alternative structures – face center cube, edge center cube, and vertex cube, represented by FCC, ECC, and VC, respectively, are created using a combination of TO and AM for evaluation. This study found that it is feasible to produce lattice structures with a unit cell dimension varying from 2 to 8 mm. The smallest unit cell dimension that can be produced chiefly depends on the size of the metal powder particles. It is challenging to remove powders with large particles trapped inside small unit cells. Additionally, the extended distance of the overhang region makes constructing unit cells more significant than 8 mm in size challenging. After 15 iterations, an equivalent volume fraction objective's topology-optimized lattice structure unit is created, as depicted in Fig. 4.3 [29]. It is also observed that in the case of the VC structure, it contains a small gap between the adjacent lattice structure units and the VC Structure, as shown in Fig. 4.4. This is due to the fact that taking OT into account only targets a single cube, and ensures full incorporation of the load position.

In a different work, SLM was used to create lattice cells having vertical and cross struts. According to a report, it is challenging to build lattice systems with enormous cell sizes (>5 mm) because of the tendency of their struts to “slag” during production [30]. Another study successfully manufactured three distinct lattice structures – cubic, octet, and TPMS gyroid – using SLM in high-porosity SS316L intended for implant applications to bioimitate real bone [31]. According to the proposed model, mechanical qualities can be predicted or created using relative densities. The findings show that these structures had excellent biocompatibility and a suitable Young's modulus.

To create hierarchical lattice microstructures, a parametric concept design and modeling method, based on density-based topology optimization, was suggested [19]. Two

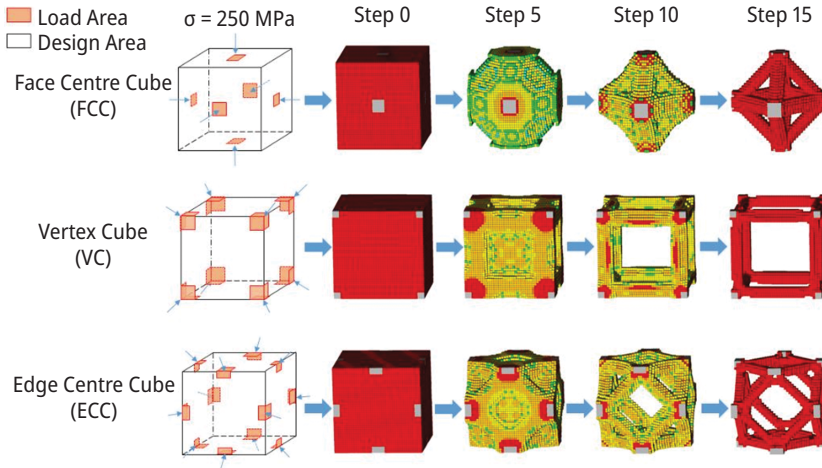


Fig. 4.3: Topologically optimized strut-based unit cells [32].

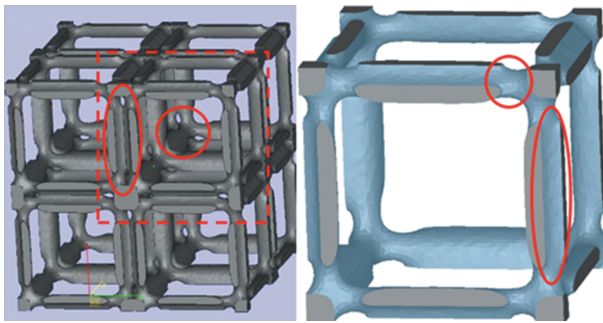


Fig. 4.4: Defects of vertex cube lattice structure [32].

design variables were used in this work to stabilize the structure's structural presentation and computing effectiveness: the mathematical formulation and the parameterized interpolation for lattice material model. The outcome demonstrates that, compared to uniform lattice microstructures, the developed hierarchical architectures provide good manufacturability and, noticeably, better structural performance. Concurrent optimization has been successfully implemented in designing multimaterial/multiscale structures in AM. In this regard, Duan et al. [33] developed a useful methodology for structuring multiscale and multimaterial composite anisotropic penalization designs in fiber-reinforced composites. By considering the collaboration between design and manufacture through additive printing, this numerical study provides a novel execution technique for lightweight, multiscale, and multimaterial design optimization of composite materials.

Numerical optimization of ground lattice structures is another frequently used method for designing lattice structures. A unique design strategy for producing peri-

odic lattice structures was put forth by Tang et al. [34] using the bidirectional evolutionary structural optimization (BESO) technique. A modified version of the standard BESO technique was used to improve the dimensional dispersion of the lattice support. The lattice structure was employed to fill in the intermediate relative density and the support areas, and the solid structure was obtained from the TO result. Dong et al. [35] employed the BESO approach to make optimized solid lattice hybrid design. For the construction of lattice structures, the force density method, which is an alternative to BESO-based technique, was used.

4.2.3 Topology optimization of self-supporting lattice structure

The geometrical design of support structures can impact the manufacturability and the removal of support structure and surface roughness left in the region. It was discovered from various earlier studies that the building platform temperature affects the behavior of the support structure. While inadequate support structures may not be able to sustain residual stresses produced due to the forces and avoid layer deformation, excessive support will increase material use, build time, and the time required to remove it. The AM processes and the products they produce depend heavily on the proper choice of support structure design [36]. Due to its complicated geometry and topology, a lattice structure is typically challenging to manufacture using traditional manufacturing techniques. The creation of lattice structures has become more straightforward, thanks to the development of AM technology [37]. However, AM still cannot directly build the overhanging surfaces of lattice structures; instead, different sustaining structures are required, which are often complex to eliminate.

Two basic categories of design techniques for self-supporting lattice structures exist. Creating self-supporting cells is an essential focus of the algorithms in the first category [29, 38]. The design domain can be filled with self-supporting unit cells using these algorithms. Still, it is challenging to extend these techniques to take the design performance of the complete structure into account. Algorithms in the second category have considered the entire structure's performance. Recently, McConaha et al. [39] suggested a lattice density optimization technique to increase the structure's stiffness, and a filtering technique to remove the different lattices for preserving the structure's ability to support itself during AM construction.

Yang et al. [40] introduced a self-supporting lattice that employs TO techniques to provide high mechanical strength at a low material cost. They employed it as the infill structure in a particular double-sided metal mirror. Without any inner support, the proposed gradient lattice was produced utilizing the SLM technique and an algorithm. According to computational and experimental results, the suggested lattice design has higher mechanical properties and a lower material cost. The printed benchmark samples with different vertical angles are shown in Fig. 4.5. With a vertical angle greater than 40, it demonstrates that the printed quality of the overhanging surface is sufficient.

Figure 4.6 displays manufactured SG (Size Gradient) and SDG (Size and Diameter Gradient)-infilled lattice structure design that mirrors without using any inner support material. Static compression studies reveal that the SDG-infilled mirror exhibits significantly improved mechanical properties despite using 20% less material than the original version. Three classes of self-supporting AM lattices, with three-, four-, and sixfold rotating symmetries, were designed and created as shown in Fig. 4.7, using the SLM approach in a different study [29].

The nodal displacement method derives the self-supported lattice's elastic constitutive relation. Sacrificial support structures are frequently used in metal-AM of complicated components, with overhangs to hold the item during the process. Concurrently built structures prevent thermal load-induced distortion/curling by attaching the over-

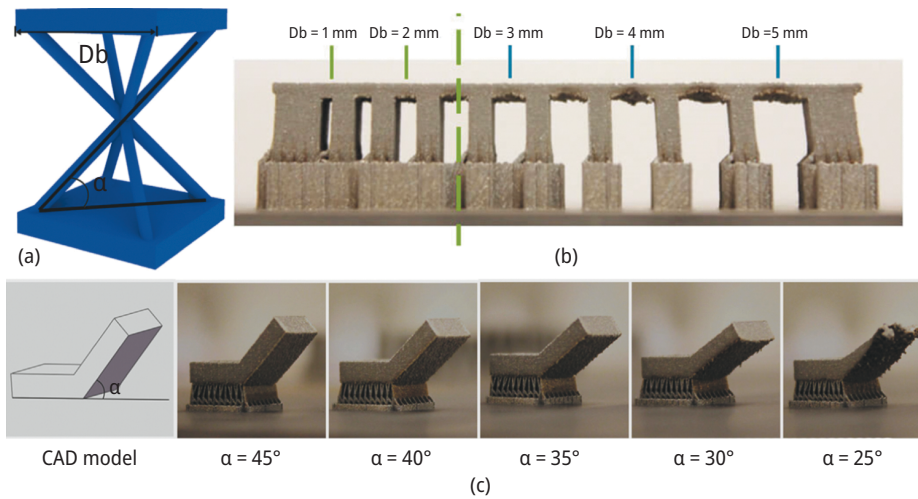


Fig. 4.5: (a) Self-supporting lattice structures, (b) manufacturability test with different bridge distances, and (c) manufacturability test with different vertical angles [40].

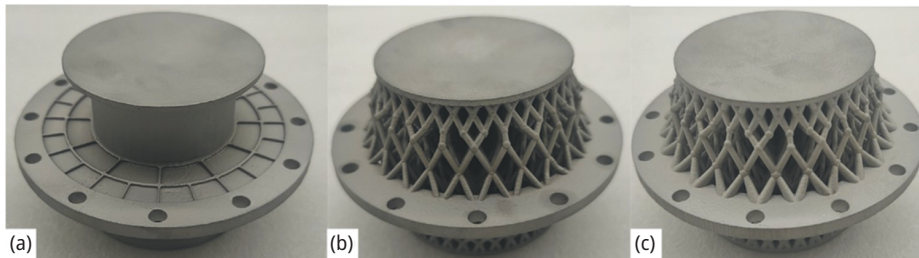


Fig. 4.6: The samples produced using SLM include (a) original mirror and (b, c) SG and SDG lattice infilled mirror, respectively [40].

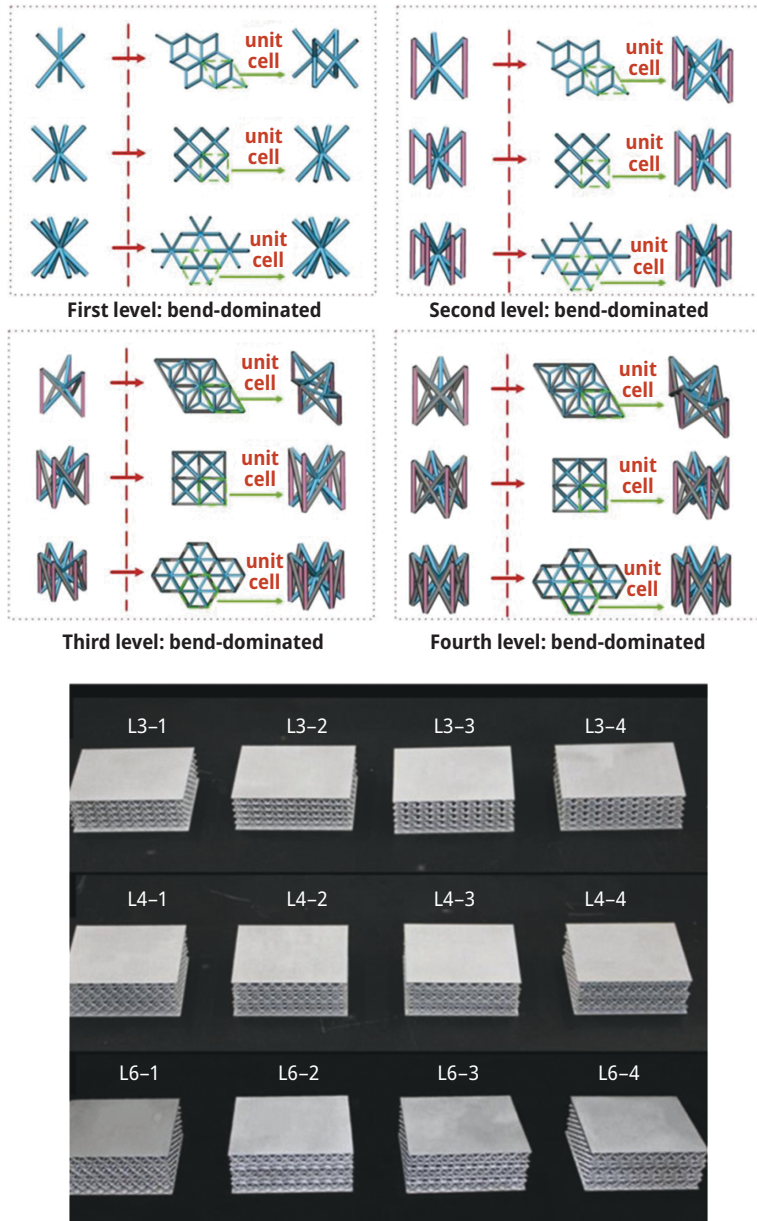


Fig. 4.7: (a) Translational symmetry of the unit cells and (b) self-supporting specimen fabricated by SLM [29].

hang shape to the base plate. They are required, but have a restriction on the kinds of geometries the processes can generate.

4.3 Machine learning-integrated DfAM

ML is “allowing computers to carry out problem-solving tasks without being particularly programmed to do so.” ML approaches have increased dramatically in recent years than in the past several years due to the accessibility of enormous quantity of data, technological breakthroughs, and better capabilities of readily available ML tools [41–43]. Additionally, ML has been applied to AM for various purposes, such as processing method improvement, material property forecasting, dimensional precision analysis, and product defect detection. Much of earlier research has mainly focused on implementing ML to enhance the product design for AM processes with the necessary property requirements. Modern ML for materials design and AM techniques have much untapped potential for collaboration.

The various ML techniques adopted in DfAM include artificial neuron network (ANN) [44, 45], multistage Bayesian surrogate models [46], surfel convolutional neural network (CNN) [47], computational fluid dynamics model [48], support vector machine (SVM) [49], inductive design exploration method, and particle swarm optimization method [50]. DfAM fundamentally diverges from conventional products design concepts due to its limitless design freedom. Due to the speed at which ML-based output-input design may be constructed, ML-based DfAM be able to attain reversed design using input-output data without complex relationship equations. Therefore, even though data is created as structure-property interactions, relationships between properties and structures can be effectively modeled. Furthermore, ML-based models practically have no constraints on the complexity of the design challenge if enough data is provided. Here, the uses of ML in DfAM will be explained in terms of two different characteristic: topology and material design. Since ML has recently advanced, material scientists and engineers can now design novel metamaterials [51] instead of just predicting material properties [52]. Numerous research studies have shown that AM methods may also materialize previously impractical designs.

An automated method was proposed for finding optimal geometries for elastic materials from the specifications given by ML and experimentally demonstrated using the polyether elastic material in a SLS process, as shown in Fig. 4.8. It is envisioned that the system can produce a custom microstructure that adheres to the requirement using ML and properties of the elastic materials.

Gu et al. [53] fabricated the ML-proposed bioinspired hierarchical composite design 3D model through 3D printing with predictable tensile strength and toughness. CNNs are used to forecast the characteristics of composite materials, and results indicate that the ML model can provide an efficient design. This study builds up blocks

using soft and hard materials randomly assigned to 8×8 arrays and then simulated to create a training model. The tensile and toughness students were conducted to evaluate the ML-generated design performance. Figure 4.9 represents the strength and toughness behavior of ML-designed 3D-model with other design models. The findings indicate that the ideal hierarchical composite created by ML is around 25 times stronger than raw material and about 40 times more potent than soft material.

Jiang et al. [55] created an approach for choosing the best design geometries for an ML implementation in AM to achieve the desired features, such as stress-strain curves. This study considered the stress, strain, range of motion, and maximum tor-

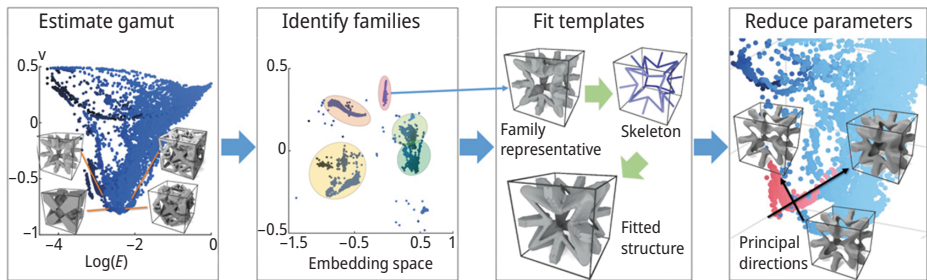


Fig. 4.8: A computational microstructure of the preferred elastic material properties [54].

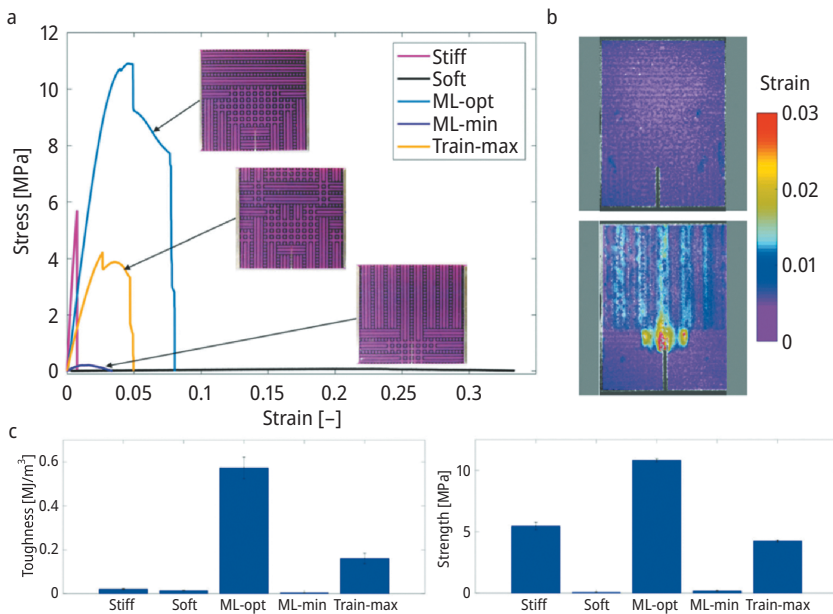


Fig. 4.9: (a) Stress-strain response, (b) strain field plots, and (c) toughness and strength for the different designs fabricated by AM [53].

que in two orientations for the evaluation. A neural network (NN) was created to specify the design constraint for a pre-selected unit cell to fulfill these objectives. Another issue with DfAM is knowledge distribution, which involves teaching designers how to create their parts as effectively as possible for manufacturing, utilizing AM technologies [46]. Tools for designers are becoming more and more necessary as the number of AM-specific design aspects increases: Such tools have been developed with the help of ML. The growing amount of AM-specific design tools rectifies the problem of knowledge dissemination for designers in DfAM to learn AM design features [56]. Table 4.1 summarizes the different ML techniques used in various AM processes with DfAM considerations.

Tab. 4.1: Summary of ML approach in AM-DfAM.

S. no.	ML technique used	AM technique used	Summary/findings/objectives	Reference
1	Machine learning (ML)	WAAM	Predictive models and algorithms successfully developed to identify the deposited layer defects	[57]
2	Physics-guided ML	PBF	Enhanced the concept of process–structure–property	[58]
3	Extreme gradient boosting (XGBoost)	DED	Optimized outstanding prediction on the melt pool shape	[59]
4	Black-box machine learning	AJP	Facilitate precise control of printed film thickness	[60]
5	Gradient boost and AdaBoost	PBF	Predict the mechanical characteristics of items made of polyamide 2200	[61]
6	Multilayer perception (MLP)	FDM	To forecast the longest printable bridge and reduce support waste	[62]
7	Adaptive-network-based fuzzy inference system (ANFIS)	SLM	“Process-based” and “property-based” models to forecast high cycle fatigue life	[63]
8	Support vector machines (SVMs)	EBM	Create a process map from a tiny dataset	[64]
9	Gaussian process (GP)	SLM	Create a process map and forecast the depth of the melt pool	[64]
10	Recurrent neural networks (RNNs)	DED	Predict the complex parts of high-dimensional thermal history during printing	[65]

Tab. 4.1 (continued)

S. no.	ML technique used	AM technique used	Summary/findings/objectives	Reference
11	Random forest (RF)	SLM	Connect the process variables to pore formation	[66]
12	<i>k</i> -Means unsupervised clustering	MEX	Estimate the geometric precision of printed items	[67]

Note: WAAM, wire arc additive manufacturing; PBF, powder bed fusion; DED, directed energy deposition; AJP, aerosol jet printing; FDM, fusion deposition modelling; SLM, selective laser melting; EBM, electron beam melting; MEX, material extrusion.

There is presently little study on applying ML to topology design for AM. A hybrid ML algorithm is proposed for designing 3D-printed car components through a case study by Yao et al. [56]. The proposed method provides feasible conceptual design solutions for inexperienced designers, with the help of using hierarchical clustering with SVMs.

4.4 Summary and conclusion

- Future high-performance, efficient end-use AM parts will be built on the foundation of structural optimization with DfAM considerations. These interdependencies have been highlighted by utilizing TO and latticing lightweight strategies.
- It is encouraging that TO for AM algorithms have been incorporated into commercial codes; this demonstrates the industry's strong push for improved “design for AM” capabilities.
- Topology optimization was used to determine the ideal density distribution, subsequently incorporated into the explicit cellular structure throughout the AM process.
- Many parts, needing lightweight and strong strength, can incorporate topology-optimized lattice into any irregular design domain. In particular, this additional self-supporting characteristic allows for the full unleashing of AM's exceptional manufacturability.
- Additionally, integrating computational structure design techniques and AM technology opens up the opportunity of creating structures with much functionality, such as high strength, high thermal conductivity, and vibration resistance.
- For resolving complex AM designs, knowledge-based ML techniques are becoming increasingly crucial and necessary for DfAM. Additionally, the applicability of ML to engineering problems is often challenged.

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Sampath Boopathi* and Parveen Kumar

5 Advanced bioprinting processes using additive manufacturing technologies: revolutionizing tissue engineering

Abstract: Advanced bioprinting processes enable precise deposition of cells, biomaterials, and bioactive agents to fabricate complex three-dimensional structures that mimic native tissues. Key advancements include multimaterial bioprinting, integration of microfluidics and nanotechnology, 4D bioprinting, and scaffold design and optimization techniques. It has revolutionized tissue engineering and regenerative medicine by providing spatial control over cell placement, creating biomimetic architectures, and incorporating bioactive cues. It has also enabled the development of disease models for drug screening, tissue models for studying biological processes, and the potential for organ transplantation. Advanced bioprinting processes have revolutionized tissue engineering and regenerative medicine, offering unprecedented control over tissue fabrication. The future of bioprinting is bright, as it has great potential applications in areas like customized medicine and organ transplantation.

Keywords: Bioprinting, additive manufacturing, tissue engineering, regenerative medicine, advanced bioprinting processes

5.1 Introduction

Bioprinting is an innovative technology that combines principles of additive manufacturing, tissue engineering, and regenerative medicine to create three-dimensional structures with living cells. It involves the precise deposition of bioinks composed of living cells, biomaterials, and growth factors to generate complex tissue-like structures that mimic the architecture and functionality of native tissues and organs. Additive manufacturing is a broader term that encompasses various techniques used to build three-dimensional objects. Bioprinting is a specific application of additive manufacturing that focuses on creating biological structures. Tissue engineering is a multidisciplinary field that aims to repair, replace, or regenerate damaged or diseased tissues and organs. Bioprinting plays

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a crucial role in tissue engineering by enabling the fabrication of intricate tissue constructs with controlled cell placement and organization [1].

Regenerative medicine is a branch of medicine that seeks to restore, replace, or regenerate damaged tissues or organs. Bioprinting provides a platform to create patient-specific tissues and organs that can be transplanted. Advanced bioprinting processes involve the development of novel bioinks, optimized printing parameters, advanced printing platforms, and integration of bioprinted tissues with the host system. Bioprinting, additive manufacturing, tissue engineering, regenerative medicine, and advanced bioprinting processes are revolutionizing healthcare by enabling the production of personalized, functional tissues and organs for transplantation, disease modeling, drug screening, and so on. The significance of bioprinting in tissue engineering and regenerative medicine is discussed below [1]:

- **Precise cell placement:** Bioprinting allows for the precise positioning of cells in three-dimensional structures, enabling the creation of complex tissue architectures. This level of control is essential for mimicking the native tissue's structure and function.
- **Patient-specific constructs:** Bioprinting enables the fabrication of personalized tissue constructs tailored to individual patients. By using a patient's own cells, the risk of immune rejection is reduced, increasing the success rate of transplants.
- **Biomimetic tissue models:** Bioprinting can produce tissue models that closely mimic the physiological and pathological conditions, allowing researchers to study diseases and test potential treatments more accurately. This technology has the potential to revolutionize drug discovery and development processes.
- **Organ replacement:** The shortage of organ donors is a significant problem in healthcare. Bioprinting holds the promise of creating functional organs on-demand, potentially eliminating the need for transplantation waiting lists and reducing organ rejection rates.
- **Accelerated healing:** Bioprinting can create scaffolds with biomaterials that provide structural support and deliver growth factors, cytokines, and other bioactive molecules to promote tissue regeneration. This can enhance the healing process and aid in the repair of damaged tissues.
- **Customizable implants:** With bioprinting, implants and prosthetics can be customized to fit specific patient needs. This customization improves patient comfort, functionality, and overall treatment outcomes.
- **Reduced animal testing:** By using bioprinted tissue models, the reliance on animal testing can be reduced, leading to more ethical research practices and potentially accelerating the development of new treatments.
- **Translational potential:** Bioprinting has the potential to bridge the gap between laboratory research and clinical applications by combining advances in bioprinting technology with tissue engineering and regenerative medicine.

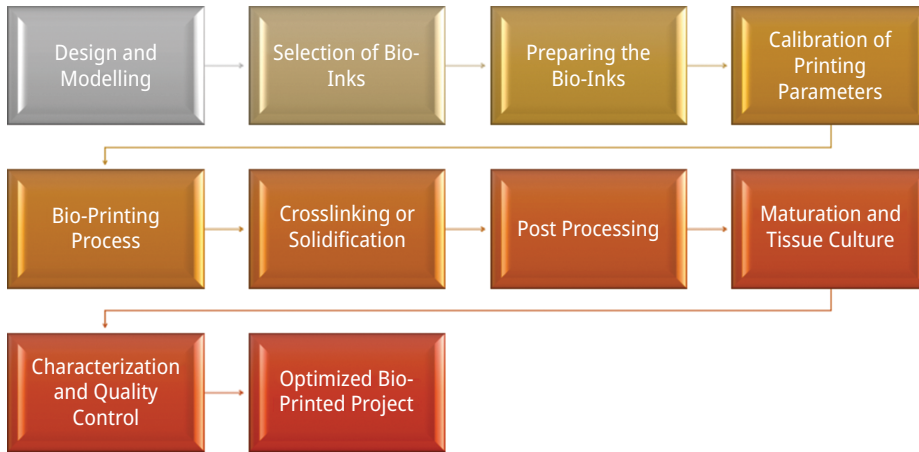


Fig. 5.1: Procedure for additive manufacturing technologies in bioprinting.

Bioprinting offers unprecedented opportunities for tissue engineering and regenerative medicine [2]. The procedure for additive manufacturing technologies in bioprinting process is illustrated in Fig. 5.1.

- **Design and modeling:** The first step is to create a digital design or model of the desired tissue or organ using computer-aided design (CAD) software. This design includes the desired shape, size, and internal architecture of the construct.
- **Selection of bioinks:** Bioinks are the materials used in bioprinting, typically composed of living cells, biomaterials, and growth factors. The selection of appropriate bioinks depends on the target tissue or organ, desired functionality, and compatibility with the bioprinting technology being used.
- **Preparing the bioinks:** The chosen bioinks are prepared by isolating and expanding the desired cell types, mixing them with suitable biomaterials, and incorporating growth factors or other bioactive molecules as required. The bioink mixture should have suitable viscosity and mechanical properties to enable proper printing.
- **Calibration of printing parameters:** The bioprinter needs to be calibrated to ensure precise deposition of the bioink. This includes setting the appropriate printing speed, temperature, pressure, and layer thickness to achieve the desired resolution and accuracy.
- **Bioprinting process:** Once the bioinks and printer parameters are ready, the actual bioprinting process begins. The bioprinter deposits the bioink layer by layer according to the digital design. Various bioprinting techniques can be used, including extrusion-based, droplet-based, or laser-assisted methods. Each technique has its advantages and limitations, and the choice depends on the specific application.
- **Cross-linking or solidification:** After each layer is deposited, some bioprinting techniques require cross-linking or solidification of the bioinks to maintain the

structural integrity of the construct. This can be achieved through different methods such as UV light exposure, temperature change, or chemical reactions.

- **Post-processing:** Once the bioprinting process is complete, post-processing steps may be necessary. These can include removing any supporting materials, applying additional treatments or coatings to enhance cell viability and functionality, and optimizing the construct for specific applications.
- **Maturation and tissue culture:** After bioprinting, the construct is typically placed in a controlled environment, such as a bioreactor or an incubator, to allow the cells to mature and develop tissue-like characteristics. This involves providing suitable nutrient supply, oxygenation, and mechanical stimulation to promote cell growth, organization, and functionality.
- **Characterization and quality control:** Throughout the bioprinting process, it is important to assess the quality and viability of the printed construct. Various characterization techniques, such as imaging, histological analysis, and functional assays, are used to evaluate cell viability, tissue architecture, mechanical properties, and biological functionality.
- **Application-specific optimization:** Depending on the intended application, additional optimization steps may be required. This can involve further tissue maturation, integration with other biomaterials or tissues, or functionalization of the construct to enhance specific properties.

5.2 Bioink development

Bioink development is essential for bioprinting to ensure viability, functionality, and integration of printed constructs [3].

Cell compatibility: Bioinks should support the survival, proliferation, and functionality of the encapsulated cells. This involves selecting or developing biomaterials that are bio-compatible and nontoxic to the cells. Natural polymers such as alginate, collagen, gelatin, hyaluronic acid, and synthetic polymers like polyethylene glycol or polycaprolactone (PCL) are commonly used as bioink components.

Rheological properties: Bioinks should possess suitable rheological properties to enable proper extrusion, deposition, and shaping during the printing process. Rheological parameters, such as viscosity, shear thinning behavior, and gelation kinetics, need to be optimized for each specific bioprinting technique. This can be achieved by adjusting the concentration, molecular weight, cross-linking density, or ratio of different components in the bioink.

Structural integrity: Bioinks should provide mechanical support to the printed construct and maintain its structural integrity during and after printing. This involves opti-

mizing the mechanical properties of the bioink, such as stiffness, elasticity, and tensile strength, to match the target tissue or organ. Reinforcing agents like microfibers, nanoparticles, or bioactive ceramics can be incorporated into the bioink to enhance its mechanical properties.

Bioactive factors: Bioinks can be supplemented with bioactive factors, such as growth factors, cytokines, or small molecules, to promote cell behavior, tissue regeneration, and functional tissue development. These factors can be incorporated into the bioink matrix or encapsulated within microcarriers, microparticles, or hydrogels within the bioink.

Printability and resolution: Bioink formulations need to be optimized for the specific bioprinting technique being used. For example, viscosity, cross-linking kinetics, and nozzle size must be adjusted to enable precise and controlled deposition of the bioink. Advanced techniques like multimaterial or gradient bioprinting may require the development of bioinks with multiple components or varying compositions to achieve the desired complexity and functionality.

Post-printing maturation: After bioprinting, bioinks should provide an environment conducive to cell maturation, tissue development, and integration with the host. This can involve incorporating stimuli-responsive elements into the bioink, such as photoresponsive or thermoresponsive materials, to enable further cross-linking, cell alignment, or release of encapsulated bioactive factors after printing.

Biodegradability and biocompatibility: Depending on the application, bioinks may need to degrade over time, allowing the cells to remodel the tissue and replace the

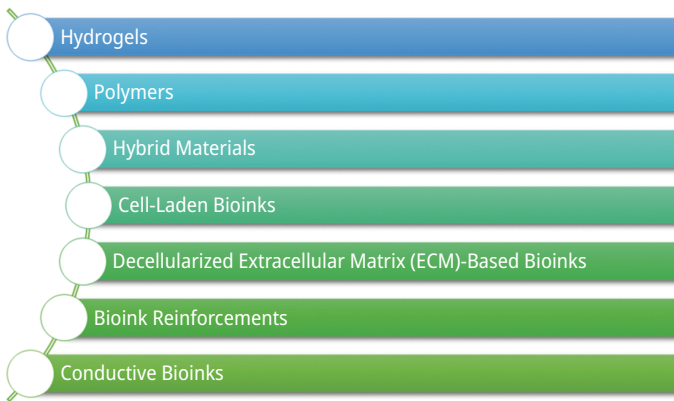


Fig. 5.2: Types of bioinks used in bioprinting process.

scaffold. The degradation rate and byproducts should be carefully controlled to ensure biocompatibility and minimize any adverse effects on the surrounding tissue.

5.2.1 Types of bioinks

Bioinks are divided into three categories: hydrogels, polymers, and hybrid materials, which are used in bioprinting [4]. The various types of bioinks used for the bioprinting processes are illustrated in Fig. 5.2.

Hydrogels: Hydrogels are water-swollen polymer networks that provide a three-dimensional environment for encapsulating cells and supporting their growth.

- **Natural hydrogels:** Natural polymers such as alginate, collagen, gelatin, HA, chitosan, and fibrin offer biocompatibility, cell adhesion sites, and biochemical cues for cell behavior.
- **Synthetic hydrogels:** Synthetic hydrogels can be modified to create cell-friendly environments with tunable mechanical properties, degradation rates, and adhesion ligands.
- **Polymers:** Polymers are macromolecules that can be used as bioinks to provide structural support and regulate cell behavior.
 - **Biodegradable polymers:** Examples include PCL, poly(lactic acid), poly(glycolic acid), and their copolymers. These polymers degrade over time, allowing for tissue regeneration and remodeling.
 - **Thermoplastics:** Thermoplastic polymers like polycarbonate, polyether ether ketone, and polystyrene offer high mechanical strength and stability. They can be used in extrusion-based bioprinting techniques.
- **Hybrid materials:** Hybrid bioinks are composed of a combination of different biomaterials, enhancing their properties and functionalities. They can be natural or synthetic, nanoparticles or bioactive molecules, and can be tailored for specific applications.
 - **Hydrogel-polymer hybrids:** Combining hydrogels with polymers can improve mechanical strength and cell support, such as by reinforcing a hydrogel with a polymer mesh to enhance stability.
 - **Nanocomposite bioinks:** Nanoparticles can be incorporated into bioinks to enhance mechanical properties, electrical conductivity, or cellular responses.
 - **Bioactive factor-loaded bioinks:** Hybrid bioinks can be engineered to incorporate bioactive factors to provide controlled release and enhance tissue regeneration or cellular behaviors.
- **Cell-laden bioinks:** Cell-laden bioinks are formulated to incorporate living cells within the bioink matrix, using hydrogels or polymers as a scaffold to support cell viability and promote their proliferation and differentiation. They enable the printing of living tissues with embedded cells, facilitating the formation of functional tissue structures.

- **Decellularized extracellular matrix (ECM)-based bioinks:** ECM-based bioinks are derived from natural tissues or organs that have been decellularized, providing a biomimetic environment for cell adhesion, migration, and tissue regeneration. They can be obtained from animal tissues or plant-based materials.
- **Bioink reinforcements:** In some cases, bioinks can be reinforced with additional materials to enhance mechanical properties. Reinforcing agents like microfibers, nanoparticles, or bioactive ceramics can be incorporated into the bioink to improve structural integrity, stiffness, and tensile strength. These reinforcements can be aligned to mimic tissue architectures or provide specific functionalities.
- **Conductive bioinks:** Conductive bioinks contain materials that possess electrical conductivity, such as carbon nanotubes or graphene. These bioinks are used to create functional tissues with electrical signaling capabilities. Conductive bioinks are particularly relevant in bioprinting applications involving neural tissue, cardiac tissue, or bioelectronic devices.
- **Self-healing bioinks:** Self-healing bioinks are designed to repair or recover from structural damage after printing. They incorporate self-healing mechanisms such as encapsulating microcapsules with healing agents or dynamic bonding interactions, allowing them to reform and regain their structural integrity when subjected to mechanical stress or damage.
- **Bioinks for vascularization:** Bioinks are developed to create perfusable channels or networks that mimic blood vessels, which can include sacrificial materials that are then removed to form functional vasculature.

5.3 Functionalization of bioinks with growth factors and bioactive agents

Functionalization of bioinks with growth factors and bioactive agents is essential for bioprinting to enhance cellular behavior, tissue regeneration, and functional tissue development [5].

Selection of growth factors and bioactive agents: The choice of growth factors and bioactive agents depends on the desired cellular responses and the specific tissue or organ being printed. Growth factors, such as transforming growth factor-beta, vascular endothelial growth factor, bone morphogenetic proteins, and insulin-like growth factor, can stimulate cell proliferation, differentiation, and tissue-specific functionality. Other bioactive agents may include cytokines, chemokines, ECM components, or small molecules with specific biological functions.

Bioink incorporation methods: Growth factors and bioactive agents can be incorporated into bioinks using various methods, such as physical entrapment, covalent con-

jugation, encapsulation, or hydrogel matrices. The appropriate incorporation method depends on the bioactive agent's properties, stability, release kinetics, and compatibility with the bioink.

Controlled release systems: Controlled release systems are used to regulate the release kinetics of growth factors and bioactive agents from the bioink. These systems can involve biodegradable microspheres, hydrogel-based reservoirs, or stimuli-responsive materials that release the bioactive agents in response to specific cues such as pH, temperature, or enzymatic activity.

Spatial patterning and gradient formation: Bioprinting techniques allow for precise spatial patterning and the creation of concentration gradients of growth factors and bioactive agents. This can be achieved by adjusting printing parameters such as nozzle deposition locations, printing speed, or multimaterial printing approaches. Spatial patterning and gradient formation enable the creation of complex tissue architectures and promote desired cellular responses in a spatially controlled manner.

Synergistic combinations: Bioinks can be functionalized with multiple growth factors or bioactive agents to create synergistic effects that enhance tissue development. By combining growth factors that act on different cellular pathways or have complementary functions, researchers can create bioactive environments that promote complex tissue formation and functionality.

Bioactivity assessment: The bioactivity of growth factors and bioactive agents in bioprinted constructs needs to be evaluated to ensure their effectiveness. Techniques such as immunoassays, bioassays, histological analysis, gene expression analysis, and functional assays can be used to assess the presence, distribution, and cellular responses induced by the incorporated bioactive agents.

5.4 Advanced bioprinting technologies

5.4.1 Multimaterial bioprinting

Multimaterial bioprinting is a technique that uses multiple bioinks or materials to create complex tissue structures with varying compositions and functionalities [6]. The work procedure of multimaterial bioprinting process is shown in Fig. 5.3.

Principles: Multimaterial bioprinting is a process of integrating different bioinks or materials into a single construct to mimic the heterogeneous nature of native tissues. It can be achieved through various methods, such as extrusion-based printing, inkjet printing, or laser-assisted printing. The selection and combination of bioinks depends on the desired tissue composition, cell types, and functional requirements.

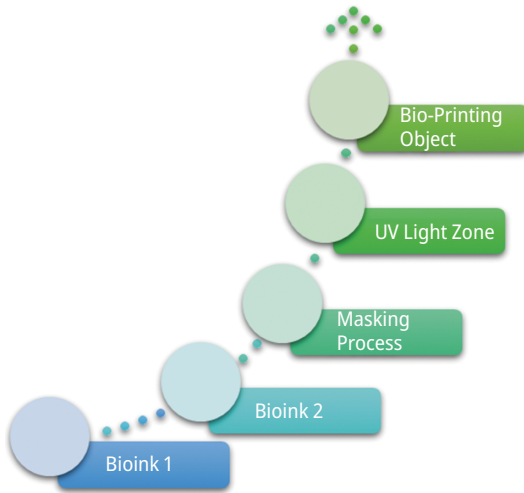


Fig. 5.3: Work procedure of multimaterial bioprinting process.

5.4.1.1 Equipment and their functions

- **Multimaterial bioprinting platform:** The bioprinting platform serves as the foundation for multimaterial bioprinting. It typically consists of a stage or build platform that allows precise positioning and movement control of the printing nozzle or printheads.
- **Printheads or nozzles:** Printheads or nozzles are responsible for dispensing the bioinks or materials onto the printing platform. They can be designed with multiple channels or nozzles to accommodate different bioinks simultaneously. Printheads enable the controlled deposition of each bioink layer by layer, forming the desired complex tissue structure.
- **Syringe or cartridge systems:** Syringe or cartridge systems are used to store and deliver the bioinks. They provide controlled pressure to extrude the bioinks through the printhead nozzles. In multimaterial bioprinting, multiple syringe or cartridge systems are used to accommodate different bioinks or materials.
- **CAD software and control system:** CAD software is used to design complex tissue structures and generate the corresponding printing instructions. The control system coordinates the movement of the printheads, deposition of bioinks, and other printing parameters based on the CAD instructions.

5.4.1.2 Applications

- **Tissue engineering:** Multimaterial bioprinting enables the fabrication of complex tissue models that mimic native tissues, facilitating tissue engineering research and regenerative medicine applications.
- **Organ-on-a-chip systems:** Multimaterial bioprinting is used to create organ-on-a-chip systems, which integrate multiple cell types, bioinks, and microfluidic channels to recreate the functionalities and interactions of organs.
- **Drug discovery and screening:** Multimaterial bioprinting can create 3D tissue constructs that mimic the physiological environment, allowing researchers to assess drug efficacy and toxicity more accurately.
- **Personalized medicine:** Multimaterial bioprinting has the potential to create tissue models tailored to individual patient needs, allowing personalized drug testing, treatment optimization, and regenerative therapies.
- **Biomedical research:** Multimaterial bioprinting enables the generation of advanced in vitro models that mimic native tissue microenvironments, providing valuable insights into cellular responses and disease mechanisms.

5.5 Bioprinting with microfluidics

Bioprinting with microfluidics is an advanced bioprinting technique that uses precise control and manipulation of fluids at the microscale to create complex tissue constructs with high spatial resolution and physiological relevance [7].

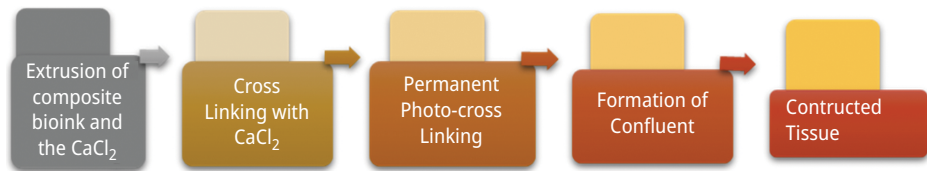


Fig. 5.4: Working principle of bioprinting process with microfluidics.

Principles: Bioprinting with microfluidics enables controlled flow and manipulation of bioinks, cells, and supporting materials at the microscale, creating microenvironments that replicate native tissues. The working principle of bioprinting process with microfluidics is illustrated in Fig. 5.4.

5.5.1 Equipment and their functions

- **Microfluidic chip:** The microfluidic chip serves as the platform for bioprinting with microfluidics. It contains a network of microchannels designed to guide the flow of bioinks and other fluids. The chip is typically fabricated using techniques such as soft lithography, micro-milling, or 3D printing.
- **Bioink loading ports:** Bioink loading ports are openings in microfluidic chips that allow for controlled loading and manipulation of bioinks within the microchannels.
- **Pneumatic or pressure control system:** A pneumatic or pressure control system is used to generate the necessary pressure or vacuum required for driving fluid flow within the microfluidic chip. It enables the precise control of fluid flow rates and pressures, facilitating the deposition of bioinks with high spatial resolution.
- **Printhead or nozzle:** The printhead or nozzle is responsible for depositing the bioinks onto the printing platform. It is connected to the microfluidic chip and enables the controlled release of bioinks at specific locations based on the microfluidic channel design.
- **Imaging system:** An imaging system, such as a microscope or high-resolution camera, is often integrated with the bioprinting setup. It allows real-time visualization and monitoring of the bioprinting process, ensuring accurate positioning and deposition of bioinks within the microfluidic chip.

5.5.2 Applications

- **Vascular tissue engineering:** Bioprinting with microfluidics enables the creation of intricate vascular networks within tissue constructs, mimicking the complex branching and connectivity of blood vessels. This technology is essential for the development of functional vascularized tissues and organs.
- **Organ-on-a-chip systems:** Microfluidics-based bioprinting is used to create organ-on-a-chip systems, allowing researchers to recreate the microenvironment and physiological functions of specific organs. This technology allows for more realistic and controlled study of organ-level functionalities, disease modeling, and drug screening.
- **High-throughput screening:** Bioprinting with microfluidics can be used for high-throughput screening of drugs or therapeutic compounds, allowing simultaneous testing of various drug candidates or conditions, reducing time and cost compared to traditional methods.
- **Tissue modeling and fundamental research:** Microfluidics-based bioprinting provides researchers with a tool to study cellular behavior, tissue development, and disease progression by creating microscale tissue models that mimic complex cellular interactions and physiological conditions.

5.6 Organ-on-a-chip bioprinting

Organ-on-a-chip bioprinting is an innovative approach that combines bioprinting technology with microfluidics to create microscale models of human organs. These systems replicate the structure and function of specific organs or organ systems in a controlled and customizable manner. An overview of the principles, equipment, functions, and applications associated with organ-on-a-chip bioprinting [8].

Principles: The principle behind organ-on-a-chip bioprinting is to recreate the micro-architecture and physiological functions of human organs using bioprinted tissue constructs integrated with microfluidic channels. By incorporating multiple cell types, biomaterials, and physiological cues, these systems aim to mimic the complexity and interactions found in native organs. The combination of bioprinting and microfluidics allows for precise control of cell positioning, tissue organization, and dynamic fluid flow, closely emulating the organ's microenvironment. The illustration for organ-on-a-chip bioprinting process is shown in Fig. 5.5.

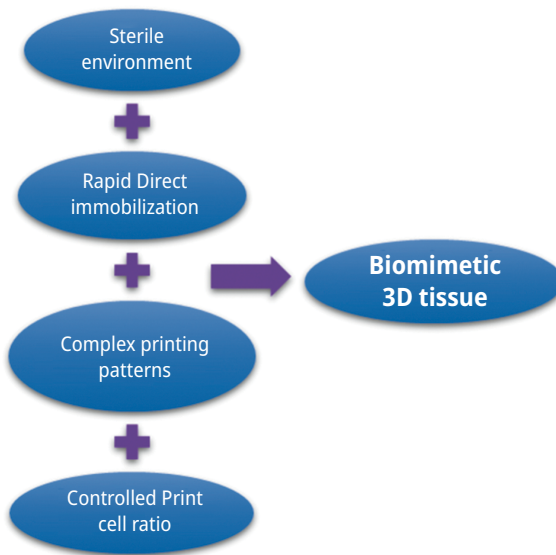


Fig. 5.5: Organ-on-a-chip bioprinting process.

5.6.1 Equipment and their functions

1. **Bioprinting system:** A bioprinting system, including the printhead or nozzle, is used to deposit bioinks and cells onto the printing platform. It enables the con-

trolled and spatially defined deposition of cells, biomaterials, and bioactive agents to construct the desired organ-specific tissue models.

2. **Microfluidic chip:** The microfluidic chip is an integral part of organ-on-a-chip bioprinting. It contains microchannels that provide a platform for fluid flow and nutrient exchange within the bioprinted tissue construct. The chip is designed to mimic the vascular network or other fluidic compartments relevant to the specific organ being studied.
3. **Pneumatic or pressure control system:** A pneumatic or pressure control system is employed to regulate fluid flow within the microfluidic chip. It ensures the precise control of flow rates, mimicking the physiological conditions of the organ and facilitating nutrient supply, waste removal, and dynamic culture environments.
4. **Imaging and sensing systems:** Imaging and sensing systems, such as microscopes, cameras, or biosensors, are often integrated into organ-on-a-chip bioprinting setups. They enable real-time monitoring and analysis of the tissue models, providing information on cell behavior, viability, and response to stimuli.

5.6.2 Applications

1. **Disease modeling and drug screening:** Organ-on-a-chip bioprinting allows researchers to create in vitro models that closely mimic the structure and function of human organs. These models are valuable tools for disease modeling, enabling the study of disease mechanisms, drug responses, and toxicity testing in a controlled and physiologically relevant setting. Organ-on-a-chip systems can be used to screen potential drug candidates, evaluate personalized therapies, and understand disease progression.
2. **Mechanistic studies:** Organ-on-a-chip bioprinting provides a platform for investigating fundamental biological processes and organ-specific functions. Researchers can gain insights into cell-cell interactions, tissue development, physiological responses, and organ-level functionalities. These studies contribute to a better understanding of organ biology, organogenesis, and tissue homeostasis.
3. **Personalized medicine:** Organ-on-a-chip bioprinting holds promise for personalized medicine applications. By using patient-specific cells and bioinks, it allows the creation of organ models tailored to individual patients. These personalized tissue models can be used to predict individual drug responses, optimize treatment strategies, and develop patient-specific therapies.
4. **Preclinical studies:** Organ-on-a-chip models created through bioprinting can be used to assess drug efficacy, safety, and pharmacokinetics before moving to human clinical trials.

5.7 4D bioprinting

4D bioprinting is the fabrication of structures that can change shape or functionality in response to external stimuli. It uses smart materials or stimuli-responsive bioinks that can undergo shape changes, self-assembly, or release of encapsulated bioactive agents. This technology has the potential to create dynamic tissue constructs that mimic native tissue behavior and adapt to their environment [9].

Principles: Bioprinting with microfluidics involves the integration of microfluidic channels into the bioprinting process, enabling controlled flow and manipulation of bioinks, cells, and supporting materials at the microscale. Researchers can create microenvironments that replicate native tissues' architecture and functionality. The working procedure for the 4D bioprinting process is shown in Fig. 5.6.

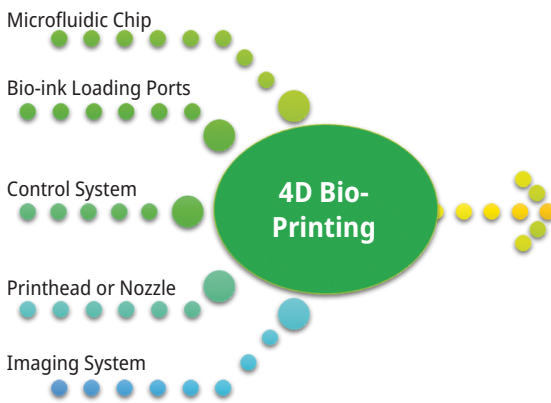


Fig. 5.6: Schematic of 4D bioprinting process.

5.7.1 Equipment and their functions

- **Microfluidic chip:** The microfluidic chip serves as the platform for bioprinting with microfluidics. It contains a network of microchannels designed to guide the flow of bioinks and other fluids. The chip is typically fabricated using techniques such as soft lithography, micro-milling, or 3D printing.
- **Bioink loading ports:** Bioink loading ports are openings in the microfluidic chip where bioinks and cells are introduced. These ports allow for controlled loading and manipulation of the bioinks within the microchannels.
- **Pneumatic or pressure control system:** A pneumatic or pressure control system is used to generate the necessary pressure or vacuum required for driving fluid

flow within the microfluidic chip. It enables the precise control of fluid flow rates and pressures, facilitating the deposition of bioinks with high spatial resolution.

- **Printhead or nozzle:** The printhead or nozzle is responsible for depositing the bioinks onto the printing platform. It is connected to the microfluidic chip and enables the controlled release of bioinks at specific locations based on the microfluidic channel design.
- **Imaging system:** An imaging system, such as a microscope or high-resolution camera, is often integrated with the bioprinting setup. It allows real-time visualization and monitoring of the bioprinting process, ensuring accurate positioning and deposition of bioinks within the microfluidic chip.

5.7.2 Applications

- **Tissue engineering:** Multi-material bioprinting enables the fabrication of complex tissue models that closely mimic native tissues, facilitating tissue engineering research and regenerative medicine applications.
- **Organ-on-a-chip systems:** Multimaterial bioprinting is used to create organ-on-a-chip systems, which integrate multiple cell types, bioinks, and microfluidic channels to recreate the functionalities and interactions found in organs. It enables precise positioning of different cell types and biomaterials within these models.
- **Drug discovery and screening:** Multimaterial bioprinting can be used to create 3D tissue constructs that mimic the physiological environment, making them suitable for drug discovery and screening. This allows researchers to assess the efficacy and toxicity of drugs in a more relevant and predictive manner.
- **Personalized medicine:** Multimaterial bioprinting has the potential to create tissue constructs tailored to individual patient needs, allowing personalized drug testing, treatment optimization, and regenerative therapies. Patient-specific bioinks and cells can be used to replicate the patient's disease condition.
- **Biomedical research:** Multi-material bioprinting is used to create advanced in vitro models that mimic native tissue microenvironments, providing valuable insights into cellular responses and disease mechanisms.

5.8 Bioprinting with nanotechnology

Bioprinting with nanotechnology is the integration of nanoscale materials into the bioprinting process, allowing for precise control over the properties and behavior of bioinks and printed structures, leading to enhanced functionality and improved tissue engineering outcomes [10].

Nanomaterials in bioinks: Nanoparticles and nanofibers can be incorporated into bioinks to improve their mechanical properties, electrical conductivity, or provide specific functionalities. Carbon nanotubes and graphene oxide can improve the conductivity of bioinks, enabling the development of bioprinted electronic devices or sensors. Electrospun nanofibers can enhance the structural integrity and strength of printed constructs.

Nanoscale cues for cell guidance: Nanotechnology can be used to create nanoscale features or patterns on the surface of printed structures, which can serve as guidance cues for cells, influencing their behavior, alignment, and tissue regeneration. These features can direct cell adhesion, migration, and differentiation, promoting desired tissue formation.

Drug delivery and therapeutics: Nanotechnology offers controlled and targeted drug delivery within bioprinted constructs. Nanoparticles can be loaded with drugs or bioactive agents and incorporated into bioinks, releasing therapeutic molecules in a controlled manner. This can improve therapeutic efficacy, reduce side effects, and enable personalized medicine approaches.

Vascularization and tissue integration: Nanotechnology can help create functional vasculature within bioprinted tissues by providing nanoscale cues or incorporating bioactive nanoparticles that promote angiogenesis. These nanoparticles can release growth factors or stimulate the recruitment of endothelial cells, facilitating the formation of vascular networks within the printed constructs. This is essential for the survival, integration, and functionality of bioprinted tissues.

Biosensors and diagnostic tools: Bioprinting with nanotechnology can enable the integration of biosensors or diagnostic tools, such as quantum dots or plasmonic nanoparticles, into bioinks to create bioprinted structures that can detect biological signals or markers. These biosensors can have applications in disease diagnosis, tissue function monitoring, or environmental sensing.

Bioprinting with nanotechnology offers exciting possibilities for tissue engineering, regenerative medicine, and biomedical applications. It enables precise control over the properties of printed constructs and provides functionalities that mimic or enhance native tissues. Research is ongoing to optimize nanotechnology-based bioprinting strategies and explore new applications for improved tissue regeneration and personalized medicine.

5.9 Scaffold design and optimization

Scaffold design and optimization are essential for bioprinting and tissue engineering. It involves mimicking native tissue architecture, incorporating desired mechanical

properties, achieving optimal porosity, and incorporating bioactive cues. These aspects are essential for successful bioprinting.

Computer-aided design (CAD) software for scaffold modeling: CAD software is used to create precise three-dimensional models of the desired scaffold structure. It allows researchers to design scaffolds with complex geometries and intricate features, ensuring accurate replication of native tissue architecture. It also provides a platform to visualize and manipulate scaffold designs before the bioprinting process [11–13].

Mimicking native tissue architecture in scaffold design: Scaffold designs aim to mimic the architecture of native tissues and organs to promote cellular activities and functionality. For example, in bone tissue engineering, scaffolds may be designed to have a hierarchical structure that mimics the natural arrangement of collagen fibers and hydroxyapatite crystals.

Incorporating porosity: Porosity is an important parameter in scaffold design as it facilitates cell infiltration, nutrient transport, and waste removal. Bioprinted scaffolds can be designed with controlled pore sizes and interconnectivity to support cell growth and tissue formation. It also influences the mechanical properties of the scaffold, allowing for an optimal balance between structural integrity and cell permeability.

Mechanical properties: Scaffold design should consider the mechanical properties required for the tissue application, such as flexibility, elasticity, or rigidity. Bioink materials, printing parameters, and scaffold architecture can be optimized to achieve the desired mechanical properties, providing adequate support for tissue development and function.

Bioactive cues: Bioactive cues are used in scaffold design to guide cell behavior and tissue regeneration. These cues can include growth factors, peptides, or biomolecules that promote cell adhesion, migration, and differentiation. Bioprinted scaffolds can be functionalized with bioactive molecules to enhance cellular interactions, tissue integration, and regeneration.

Optimization techniques: Computational modeling and experimental approaches are used to optimize scaffold design. Computational modeling allows researchers to predict and analyze scaffold properties before fabrication, while experimental techniques such as mechanical testing, cell viability assays, and tissue culture studies are used to assess and optimize the performance of bioprinted scaffolds.

5.10 Post-printing processing and maturation

Post-printing processing and maturation are essential steps in bioprinting to enhance the stability, cell proliferation, tissue maturation, and functionality of the printed constructs [14].

Cross-linking methods for bioink stabilization: Cross-linking is a process used to stabilize printed bioinks and provide structural integrity. Common methods for hydrogel-based bioinks include physical, chemical, or photo-cross-linking. Cross-linking enhances the mechanical strength and stability of the printed scaffolds, enabling cell attachment and tissue formation. It can be done using physical, chemical, or photo-cross-linking methods.

Cultivation techniques for cell proliferation and tissue maturation: The printed constructs need to be cultured in appropriate conditions to promote cell proliferation and tissue maturation. This involves placing them in bioreactors or incubators that provide nutrient supply, oxygenation, and environmental cues for cell growth. Different cultivation techniques, such as perfusion culture, dynamic culture, or co-culture systems, can be employed to mimic physiological conditions and promote tissue maturation.

Strategies for promoting vascularization in printed tissues: Vascularization is essential for the survival and functionality of large tissue constructs. Strategies to promote vascularization include incorporating bioactive cues such as growth factors or angiogenic factors into the printed scaffolds, using sacrificial materials or microchannels to create pathways for vascular ingrowth, and using post-printing cultivation techniques such as shear stress or perfusion of growth factors.

Maturation of printed tissues: Maturation of printed tissues involves the development of tissue-specific characteristics and functionality, which can be achieved through long-term culture, exposure to appropriate biochemical and mechanical cues, and the incorporation of cell-specific factors. In muscle tissue engineering, mechanical stretching or electrical stimulation can promote tissue maturation and contractility.

Assessment and characterization: Post-printing processing and maturation involve the assessment and characterization of printed constructs, including cell viability, proliferation, and differentiation. Techniques such as histological staining, immunostaining, gene expression analysis, and functional assays are used to assess tissue formation, cell phenotype, and overall construct functionality.

5.11 Case study: bioprinting of cartilage constructs for osteoarthritis treatment

Osteoarthritis is a degenerative joint disease characterized by the breakdown of cartilage, and tissue engineering approaches hold promise for cartilage regeneration. This case study explores bioprinting of cartilage constructs using additive manufacturing technologies [15, 16].

5.11.1 Methods

1. Bioink development:
 - Formulation of a bioink comprising cartilage-specific cells, such as chondrocytes or mesenchymal stem cells (MSCs), suspended in a suitable hydrogel matrix.
 - Incorporation of bioactive factors, such as growth factors or cytokines, to enhance chondrogenic differentiation and extracellular matrix production.
2. Advanced bioprinting technologies:
 - Extrusion-based printing using a bioprinter equipped with a nozzle system capable of precise cell deposition.
 - Optimization of printing parameters to ensure cell viability and proper distribution within the construct.
 - Layer-by-layer printing of the bioink to create a three-dimensional cartilage construct with defined geometry.
3. Scaffold design and optimization:
 - Generation of a scaffold design that mimics the native cartilage architecture, including appropriate pore size and interconnectivity.
 - Integration of mechanical properties, such as stiffness and elasticity, to provide structural support and mimic native tissue characteristics.
4. Post-printing processing and maturation:
 - Cross-linking of the bioink to enhance construct stability and integrity.
 - Cultivation of the printed cartilage constructs in a bioreactor system to promote cellular proliferation, extracellular matrix synthesis, and tissue maturation.
 - Optimization of culture conditions, including nutrient supply, oxygenation, and mechanical stimulation, to enhance cartilage tissue development.

5.11.2 Outcomes

The bioprinted cartilage constructs demonstrated promising results *in vitro* and *in vivo*:

- *In vitro* studies showed high cell viability, cell proliferation, and chondrogenic differentiation within the constructs.
- Animal studies demonstrated successful integration of the bioprinted constructs with the host tissue, formation of functional cartilage, and improved joint function.

Bioprinting of cartilage constructs using additive manufacturing technologies is a promising approach for osteoarthritis treatment. This case study highlights the feasibility and potential of bioprinting, which holds great promise for future regenerative medicine applications. Further research and optimization are needed for clinical translation.

5.12 Case study: bioprinting of vascularized cardiac tissue for myocardial infarction therapy

Bioprinting vascularized cardiac tissue is a potential solution for myocardial infarction therapy, and this case study explores the bioprinting of vascularized cardiac constructs using additive manufacturing technologies [17–19].

5.12.1 Methods

1. Bioink development
 - Formulation of a bioink consisting of cardiac-specific cells, such as cardiomyocytes, endothelial cells, and supporting cells, suspended in a hydrogel matrix.
 - Incorporation of bioactive factors, such as growth factors and cytokines, to enhance cell survival, angiogenesis, and tissue maturation.
2. Advanced bioprinting technologies:
 - Inkjet-based printing using a bioprinter equipped with high-resolution print heads capable of depositing multiple cell types and biomaterials.
 - Precise printing of cardiomyocytes, endothelial cells, and supporting cells in a spatially organized manner to mimic native cardiac tissue architecture.
3. Scaffold design and optimization:
 - Designing a scaffold with intricate vascular networks to enable nutrient and oxygen supply to the printed cells.
 - Optimization of scaffold properties, such as mechanical strength, porosity, and degradation kinetics, to support tissue development and remodeling.
4. Post-printing processing and maturation:
 - Incorporation of endothelial cells within the printed constructs to promote angiogenesis and blood vessel formation.
 - Cultivation of the bioprinted cardiac constructs in a bioreactor system that mimics physiological conditions, including mechanical stimulation and oxygenation.
 - Optimization of culture parameters, such as electrical stimulation and growth factor supplementation, to enhance tissue maturation and functional properties.

5.12.2 Outcomes

The bioprinted vascularized cardiac constructs demonstrated promising outcomes:

- In vitro studies revealed successful printing of multicellular cardiac structures with aligned cardiomyocytes and functional blood vessel networks.

- Animal studies demonstrated integration of the bioprinted constructs with host tissues, increased vascularization, improved cardiac function, and reduction in infarct size.

Bioprinting vascularized cardiac tissue using additive manufacturing technologies holds great potential for myocardial infarction therapy. This case study highlights the feasibility and potential of bioprinting in creating functional cardiac constructs with integrated vascular networks. Further research and optimization is needed for clinical translation, but this technology offers a promising approach to enhance cardiac regeneration and improve patient outcomes.

5.13 Limitations and emerging perspectives

Bioprinting challenges and technical limitations must be addressed to advance the field, as well as emerging trends and future directions, as well as regulatory and ethical considerations [4, 14, 20].

Addressing limitations and technical challenges in bioprinting: Bioprinting faces technical challenges that need to be addressed for wider application.

- **Cell viability and functionality:** Research is needed to ensure high cell viability and functionality after printing, such as optimizing bioink formulations and improving cell-material interactions.
- **Vascularization:** Developing strategies to promote efficient and functional vascularization within bioprinted constructs is essential for long-term survival and functionality.
- **Scale-up and manufacturing:** Bioprinting processes must be scaled up to produce larger tissue constructs suitable for clinical use, requiring consistent and reproducible results, increased printing speed, and robust manufacturing processes.

Emerging trends and future directions in advanced bioprinting technologies:

Several emerging trends and future directions are shaping the field of bioprinting.

- **Multi-material and hybrid printing:** Advances in multi-material and hybrid bioprinting enable the integration of different cell types, biomaterials, and functionalities into a single construct, enabling the fabrication of complex tissues and organs.
- **Biofabrication of functional organs:** Bioprinting is being used to fabricate functional organs for transplantation, with progress being made, but challenges remain.
- **Bioinks with enhanced properties:** Advanced bioinks with improved mechanical properties, bioactivity, and stimuli-responsiveness enable better control over printed constructs and improved tissue regeneration outcomes.

5.14 Conclusions

- Advanced bioprinting processes have revolutionized tissue engineering and regenerative medicine, with key advancements such as multi-material bioprinting, integration of microfluidics and nanotechnology, 4D bioprinting, and scaffold design and optimization techniques. These advances have enabled precise control over the printing process, improved cell viability and functionality, and enhanced biomimetic properties.
- Bioprinting has had a profound impact on tissue engineering and regenerative medicine, providing spatial control over cell placement, creating complex tissue architectures, and incorporating bioactive cues. It has also enabled the development of disease models, drug screening platforms, and personalized medicine approaches.
- Advanced bioprinting holds great promise for future developments and applications. Optimization of bioinks, such as incorporation of growth factors, nanoparticles, and bioactive agents, will enhance the functionality and regenerative potential of printed constructs. Improved vascularization strategies will enable the fabrication of larger and more complex tissues. Advancements in bioprinting technologies will continue to push the boundaries of tissue engineering.
- Bioprinting functional organs for transplantation and combining it with other cutting-edge technologies such as stem cell research, gene editing, and tissue decellularization has the potential to create complex tissues and organs with improved functionality.
- Advanced bioprinting processes have revolutionized tissue engineering and regenerative medicine by providing precise control over cell placement, scaffold design, and bioactive cues. This has had a profound impact on healthcare, opening up new possibilities for personalized medicine, organ transplantation, and improved patient outcomes.

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6 Comparative analysis of thermal characteristics and optimizing laminar flow within medical-grade 3D printers for fabrication of sterile patient-specific implants (PSIs) using computational fluid dynamics

Abstract: Medical 3D printing is a powerful tool for fabricating patient-specific implants (PSIs) that offer reduced surgical time, enhanced clinical outcomes, and cost-effectiveness. These implants interact with the human body and must remain sterile and uncontaminated.

Polyether-ether-ketone (PEEK), an excellent biomaterial, is widely adopted for 3D printing of medical implants but requires high-temperature conditions. This study explores the feasibility of a 3D printer producing sterile implants ready for direct implantation in the body.

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Two configurations of a medical-grade 3D printing machine are proposed, aiming to eliminate velocity fluctuations and eddy formations, to prevent contamination while optimizing heat transfer in the overall system during printing of PEEK implants. Computational fluid dynamics is used to investigate fluid flow dynamics to achieve laminar flow and sterility.

Simulation results showed that both configurations could achieve laminar flow inside the 3D printer, ensuring sterility, while maintaining a suitable temperature for producing PEEK implants. The results showed that temperature changes inside the chamber and design changes were successful at regulating airflow and enhancing heat transfer.

The successful design of the medical-grade 3D printing machine configurations, coupled with simulation results, provided valuable insights for further development and improvement of medical-grade 3D printing machines for PEEK implant production.

Keywords: 3D printer, heated chamber, CFD, Reynolds number, laminar flow, turbulent flow, conduction, convection, heat transfer, PEEK

6.1 Introduction

Three-dimensional (3D) printing is a revolutionary technology that is having a significant impact on society and the economy and will continue to do so in the future. This technique, which first emerged in the 1980s and was initially only applicable to small-scale manufacturing, is currently being employed for massive construction projects [1]. Many new materials and printing techniques have been developed, with advancements in the process of 3D printing [2]. It has become an increasingly popular fabrication method, being employed across various industries due to its design flexibility, allowing it to produce products, limited only by imagination [3]. This trend is also evident in medical applications, facilitating the easy construction of biomimetic biological structures [4]. There are several applications for 3D printing in surgical research and practice, including the development of PSIs and anatomical models for surgical planning and guidance [5, 6]. Due to improvements in 3D printing and diagnostic imaging techniques, surgeons now prefer 3D-printed PSIs since they provide improved fit and aesthetics, and take less time and money to fabricate. It is viable as greater design freedom is possible with 3D printing, which can produce parts with complex geometries [7].

The main prerequisite for additive manufacturing (AM) techniques is a 3D physical computer-aided design (CAD) model. By adding material layer by layer, AM, also known as 3D printing, creates objects with the desired properties, directly from 3D CAD models [8, 9]. The CAD model is transferred to the AM interface, where it is first converted to a Standard Tessellation Language (STL) file, and a universal format for AM systems. The CAD model is input to the AM printer in the form of 3D data that

comes from either a conceptualized idea of an engineer or from prototypes obtained from data acquisition techniques. After undergoing some other essential operations, this 3D CAD model is made easily readable by AM systems; the STL model is divided into several 2D planes, and then the AM systems construct a structure, layer by layer in the z-direction [10, 11]. To follow a set of details from the CAD system to the AM system, an interface that can maintain geometric and additional information is essential between them. There are several CAD systems available now that immediately create a 3D CAD model, to offer input to the AM machine [11, 12].

To manufacture these PSIs using 3D printing technology, a medical-grade 3D printer is required. When printing these implants, it is crucial to prevent contamination, which can be achieved by printing in specially designed environments. The required environment depends on the material and the specific implant being fabricated. Polyether-ether-ketone (PEEK) is a high-performance biomaterial that possesses favorable physical and chemical qualities, making it well-suited for 3D printing, and a preferred material for medical implants [13].

Typically, bacterial and dust deposition, due to air swirls generated within the printer casing, are cited as the primary causes of implant contamination. Air is supplied to the casing at a temperature specific to the implant, establishing an optimal environment for printing. Eliminating air swirls or eddies can be achieved by creating a laminar flow regime inside the printing chamber [13]. A medical-grade 3D printer, unlike a conventional 3D printer, operates in a highly controlled environment, to maintain sterility. The controlled environment's features are primarily determined by the implant type and material used, but contamination prevention must be ensured.

This study explores the feasibility of a 3D printer producing sterile PSIs suitable for implantation within the human body. The maintenance of a consistent air flow and thermal management within the printing environment are important factors to consider for achieving sterility.

In the field of cranial reconstruction, 3D printing technology has shown promising results in creating PSIs that closely match the patient's unique anatomy, leading to improved outcomes and reduced complications [14]. This study demonstrated the successful development and implementation of patient-specific cranial implants using advanced 3D designing and manufacturing techniques. They used computed tomography scans to design a 3D model of the skull and cranial defect, followed by the creation of the implant using CAD software, and producing it with AM techniques. This method has the potential to enhance the treatment of unilateral cranial defects and streamline the overall treatment process. In our research, we aim to build upon these findings by examining the laminar flow characteristics within medical-grade 3D printers and evaluating their impact on implant production and sterility.

This study focuses on the design and optimisation of PEEK and Ti-6Al-4V fixture-based cranial implants. It is important to remember that the sterility of these implants is also greatly dependent on how they are made. The production of PSIs with great precision and accuracy has been made possible by AM techniques like 3D printing,

but they also create difficulties for maintaining a sterile environment while printing. To avoid contamination and guarantee the security of the implant recipient, proper control of laminar flow within the printing chamber is essential. Proper management of laminar flow within the printing chamber is crucial to prevent contamination and ensure the safety of the implant recipient [15].

Furthermore, keeping a consistent temperature distribution is difficult and important, as a material's mechanical characteristics, especially the tensile strength and print performance, vary highly at various temperatures [2, 16].

Computational fluid dynamics (CFD) can be integrated with 3D printing as a valuable resource. The mechanical engineering community uses CFD software to analyze fluid flow. Process safety and loss prevention experts use CFD simulations to improve current designs, acquire fresh perspectives, and explore potentially dangerous situations [17]. Models that effectively represent flow simulations can be generated using 3D printing and employed for product demonstrations or at trade shows to better explain designs. The model's lines depict fluid movement, while changing colors indicate variations in key factors.

Researchers have found CFD to be a powerful technique for simulating fluid flow motions, and modeling flow patterns and temperature distributions using CFD has been around for a while [18]. The community has acknowledged CFD as a helpful method for anticipating air movement in ventilated rooms. The solution of the fundamental flow equations is used to predict the flow [19].

Equations like Reynolds-averaged Navier–Stokes are employed to simulate various fluid flow challenges [20]. The shift from laminar to turbulent flow is defined by the critical Reynolds number (Re), based on the fluid and flow media's hydraulic parameters [21]. Fluid motion that exhibits erratic fluctuations in pressure and flow velocity is referred to as a turbulent flow. Conversely, laminar flow is characterized by regular fluid motion in parallel layers without disruptions. Numerous researchers have investigated the relationship between laminar or turbulent flow and airborne microbiological contamination [22]. Laminar flow is essential, since research indicates that maintaining a low contamination profile requires regular maintenance and cleaning of laminar flow hoods [23].

In a room, airflows and their transports are 3D rather than 1D. For assessing such 3D flows, CFD has been proven to be a useful technique. Because the equations are nonlinear, they can be frequently solved numerically. The CFD study necessitates a significant amount of computing power and time [24]. To analyze the heat transfer protocols and the way heat is being dissipated in a particular closed surrounding, CFD is a vital tool that can be used to get the desired value of unknowns. The heat flow can be evaluated in 3D printers with the use of CFD, which can be shown to be quite useful in boosting their working capabilities.

In this study, different configurations of a medical-grade 3D printing machine are designed for producing PSIs with different component geometries, to achieve a printing environment capable of producing sterile implants. The primary objective of this

study is to eliminate significant velocity fluctuations and eddy formations within the fluid flow domain to prevent bacterial contamination on the interface or inside the printed implants. This is achieved by examining the flow type using CFD and optimizing the system to reduce the Re , resulting in a laminar airflow domain.

Also in this chapter, we are focusing on the difference in overall temperature throughout our enclosed chamber, with variations in inlet heating fans and outlet exhaust. In light of the recent developments in 3D printing for medical applications, we will also discuss the implications of our findings on the optimization of 3D printing processes for cranial implant production, as described by [15]. By incorporating these research findings into our analysis, we aim to contribute to a more comprehensive understanding of the factors affecting the performance and reliability of 3D-printed medical devices.

6.2 Materials and methods

6.2.1 Design configurations

A medical-grade 3D printing machine was designed with the purpose of producing PSI while operating within a laminar hood. After careful consideration of various factors, two different configurations of the 3D printer were finalized, as illustrated in Fig. 6.1. These configurations differed in component geometries and the placement of inlets and outlets, aiming to minimize the turbulent intensity and maximize the laminar fluid flow throughout the system.

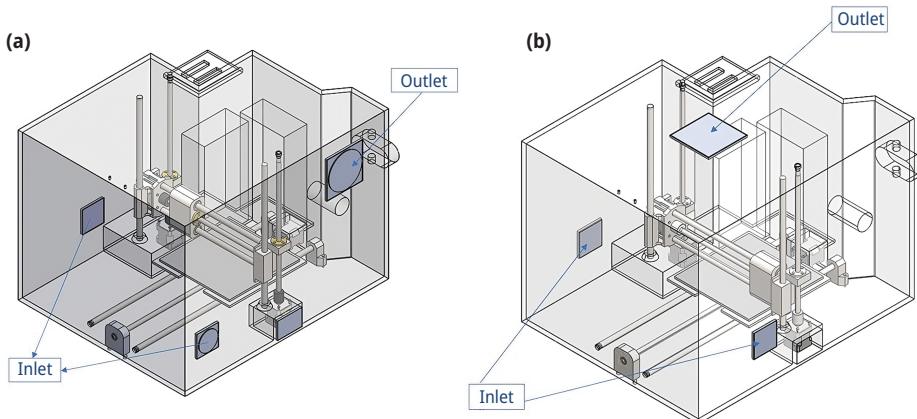


Fig. 6.1: 3D printer configurations: (a) first and (b) second.

One of the challenges in maintaining a contaminant-free environment during the printing process is the generation of large eddies and velocity variations, which can lead to the random deposition of particles on surfaces. To address this issue, the printer incorporates a structure with internal laminar flow. Laminar flow ensures that particles within the volume move in laminas, maintaining a constant direction and time.

To enhance laminar flow within the proposed printer, it was crucial to ensure that all parts, such as axis rods, motor holders, and bed supports, possessed uniformly smooth aerodynamic geometries. The Reynolds number (Re) parameter was employed to examine the type of fluid flow inside the printer casing. For proper laminar fluid flow, the desired value of Re should be less than or equal to 2,000 [25]. This ensures that the flow remains laminar and free from turbulent disturbances.

The proposed medical-grade printer operates within a temperature range of 60 to 104 °C. As the surroundings, heating elements, and heat flowing inside the chamber are at significantly different temperatures, substantial heat transfer occurs across the three systems. Convection, resulting from bulk movement among fluid particles, is the primary mode of heat transfer in this scenario.

Considering all the parameters, the two design configurations shown in Fig. 6.1 were developed, taking into account specific boundary conditions and an airflow medium to regulate the laminar boundary layer within the printer. Since the printer is intended to be placed inside a Laminar Hood, the air entering the casing exhibits minimal turbulent flow. Despite the potential formation of eddies due to air molecule interactions at the inlets, the turbulent intensity remains low, at approximately 1%, with a turbulent length of 0.004 m. The entire system operates under pressure-driven conditions, with the inlets pulling in air at a velocity of 1.2 m/s, while it escapes through a pressure opening.

In the context of medical-grade 3D printing machines, the two different configurations and the structures proposed in Fig. 6.1 are also designed to optimize heat transfer in the overall system. These configurations incorporate different component geometries and inlet/outlet configurations. The design accounts for extruder and chambers high-temperature requirements, enabling the printing of materials like PEEK without encountering breakdown or warpage issues. The thermal parameters, like the temperature of the nozzle and chamber, were carefully considered and experimentally tested to achieve optimal mechanical strength [26].

It is possible to evaluate heat transfer mechanisms computationally or experimentally. An experimental approach focuses on measuring the real physical phenomenon and obtaining the desired quantities within the bounds of experimental error. But this method can be costly, time-consuming, and sometimes impractical, particularly if the system under consideration does not exist. On the other hand, the analytical technique, including numerical analysis, provides a quick and cost-effective approach. However, the accuracy of the findings depends on the correctness of the assumptions and idealizations made during the analysis [18].

The similarities in both configurations are:

- Electronic parts are positioned outside the printing chamber and given access to their own cooling system in order to prevent them from malfunctioning as a result of the high temperatures produced during 3D printing. The reason for this is that these components were not intended to tolerate temperatures higher than 50 °C. A fan or other similar device is typically used in the forced convection cooling system to move cool air around the electronics.
- For maintaining a sterile printing environment when using PEEK, both 3D chamber printers are equipped with two hot air blow fans to regulate the temperature inside the chamber, and one low-pressure outlet.
- The gantry system and the components used are the same for both 3D printers.

The two hot fan blowers on the 3D printer configuration 1 are not facing each other; this was done to provide good air circulation to all corners of the printer, allowing for proper sterilization and a stable ambient temperature for 3D printing.

In order to ensure a steady flow of warm air to the filament, configuration 1 places a pressure outlet close to the filament spool. This positioning makes sure that the filament may be adequately warmed by the heated air. While in configuration 2 of the 3D chamber printer, the pressure outlet is located at the top to prevent any restriction in the flow of hot air. This placement allows the heated air to circulate freely within the chamber, without any obstacles that could impede the printing process.

Considering all the parameters, the two design configurations as shown in Fig. 6.1 were developed with specific boundary conditions and an airflow medium. The printer is designed to be placed inside a Laminar Hood; so the air entering the printer's casing will have a very low to negligible turbulent flow component. Even after considering the eddy formations due to the interaction of air molecules with the inlets, the turbulent intensity still comes out to be only 1% and a turbulent length of 0.004 m. The whole system is pressure-driven. The inlets pull in the air at a rate of 1.2 m/s and it escapes the casing through a pressure opening.

6.3 Materials

6.3.1 Peek 3D printing

PEEK materials have unique characteristics such as biocompatibility, nontoxicity, osteoconductivity, and noninflammatory nature that makes them compatible to be used as an implant. PEEK is a bioinert material since it has no negative reactions and does not release any toxic component into the human tissues [25]. Medical 3D printing technology provides a way to produce PSI, with advantages such as quicker operational times and better clinical outcomes at a reasonable price [8]. The medical-grade 3D

printing machine is designed focusing primarily on printing of implants made of PEEK. As a trustworthy substitute for other alloplastic materials, PEEK has begun to be utilized for reconstructive and orthopedic procedures, mainly due to its favorable biomechanical properties. One of the advantages of printing PEEK using fused deposition modeling is that practically any complex design could be produced that might not be produced with other methods [27]. But due to the PEEK's physical characteristics, 3D printing is difficult and typically requires a particular printing environment, which, if not properly taken care of, will lead to the development of inconsistencies and delamination in printed components [28]. The surrounding temperature during the printing of PEEK needs to be around 100 °C. To establish this temperature inside the printing machine chamber, heating elements in the form of hot fan blowers are used. These elements continuously supply air at a temperature of 100 °C into the chamber and the air escapes through a pressure opening, thus creating an airflow loop. To entrap this heat energy in the system, the walls of the casing are covered using an insulating material.

To withstand this high temperature, the components (x, y, z axis supports) of the 3D printing machine were fabricated using stainless steel and aluminum.

The printing of implants can only be initiated once the whole control volume is in thermal equilibrium. To attain this equilibrium, the heat supplied by the blowers needs to raise the temperature of the stainless steel parts.

6.3.2 Assumptions

To simplify the problem, the following observations and assumptions are made:

Observations:

- The temperature of the stainless steel parts plays no significant role in the printing of implants, except for the extruder and printing bed.
- The temperature of the extruder and printing bed is independently controlled using supplementary heating elements.
- Uneven temperature distribution across the temperature range of the printing environment has effects on the print, for example, uneven shrinkage or broadening of implants.

Assumptions:

- Heat conduction through solids can be neglected.
- Heat generation inside the system can be neglected (heat generated in the bed and extruder has no significant effects on the casing temperature as compared to the air temperature).
- Therefore, convection can be considered as the main mode of heat transfer.

6.4 Computational fluid dynamics

6.4.1 Finite volume method

The finite volume method is an algebraic equation-based method used for describing and evaluating partial differential equations. It involves the conversion of volume integrals containing a divergence term to surface integrals using the divergence theorem [29].

CFD analysis is performed on the 3D printer model using the software package: SolidWorks 2018. The CAD-integrated CFD package (SolidWorks Flow Simulation 2018) is used to create the finite volume model to analyze the flow properties within the printer. The analysis type is set to internal, excluding cavities without flow conditions, and gravity is included in the study. The fluid is set to air and then the computational domain was set as shown in Figs. 6.2 and 6.3. Figure 6.2(a) and (b) represents a computational domain model for first configuration. Figure 6.3(a) and (b) represents a computational domain model for second configuration. The flow of fluid is confined within a closed system of a 3D chamber printer in both configurations.

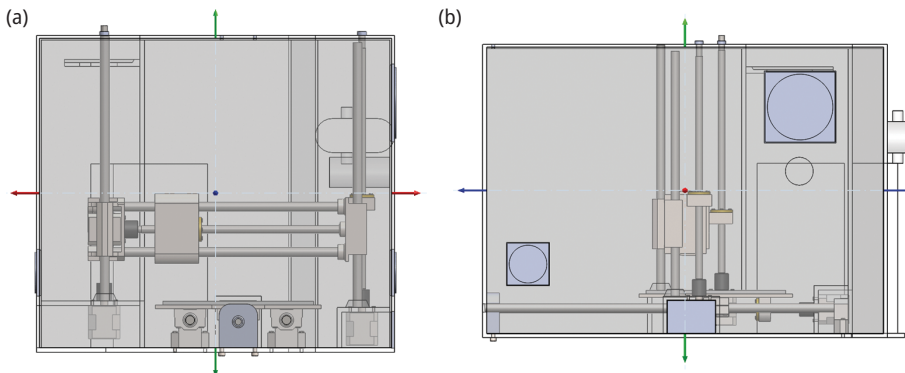


Fig. 6.2: Computational domain for the first configuration is shown: (a) front view and (b) side view.

6.4.2 Meshing

Meshing is a crucial step in producing an accurate CFD simulation. A global mesh with refinement level 6 was generated to mesh the flow regime, and local mesh of all the components was created to precisely calculate fluid interaction with solid bodies, as shown in Fig. 6.4.

A total of 6,221,440 fluid cells were generated, with 1,977,325 fluid cells interacting with the solid bodies, as detailed in Tab. 6.1.

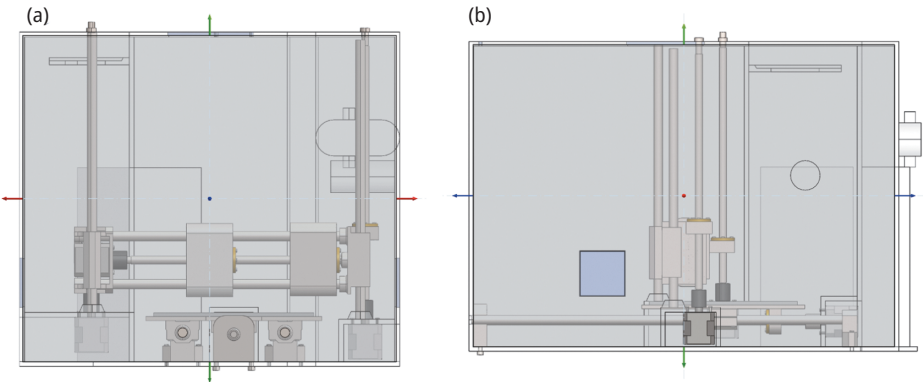


Fig. 6.3: Computational domain for the second configuration is shown: (a) front view and (b) side view.

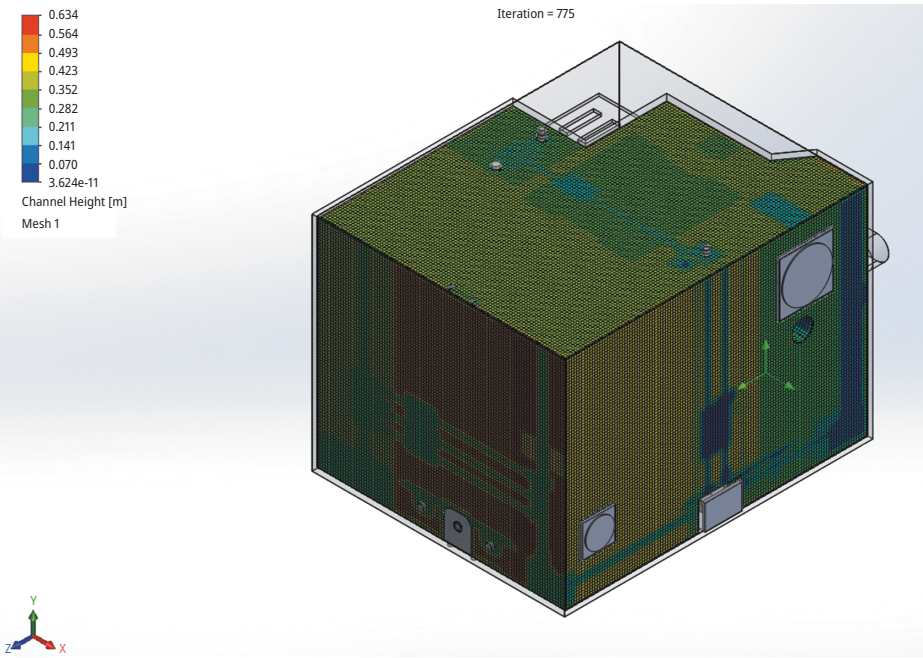


Fig. 6.4: Meshing (channel height).

Tab. 6.1: Number of total fluid cells and fluid cells contacting solids.

Configuration	Number of total fluid cells	Number of fluid cells contacting solids
First	6,221,440	1,997,325
Second	6,221,440	1,997,325

6.4.3 Flow regime

Before evaluating the flow regime, the following flow parameters were set.

- Inlet air temperature: 373.15 K (100 °C)
- Inlet velocity of air: 1.2 m/s

To estimate the flow regime, the Re of the flow in the printer's casing through a rectangular inlet [30] has been calculated using the following equation:

$$Re = \frac{\rho^* v^* d_{eq}}{\mu} \quad (6.1)$$

where $\rho = 0.9459 \text{ kg/m}^3$ is the density of air at 373.15 K;

- As $\rho = P/RT$ [31]

where P is the pressure at which air density is measured = 101,325 Pa, R is the universal gas constant of dry air = 287.058 J/kg K, T is the temperature at which air density is measured = 373.15 K; $v = 1.2 \text{ m/s}$ = velocity of air at inlet; $\mu = 2.173 \times 10^{-5} \text{ Pa s}$ is the dynamic viscosity of air at 373.15 K;

- As $\mu = aT^{1/2}/(1 + b/T) \text{ Pa s}$ [32]

where $a = 1.458 \times 10^{-6} \text{ kg/(m s K}^{1/2})$, $b = 110.4 \text{ K}$, T is the absolute temperature, $d_{eq} = (4 \times \text{area of inlet})/(\text{perimeter of inlet})$.

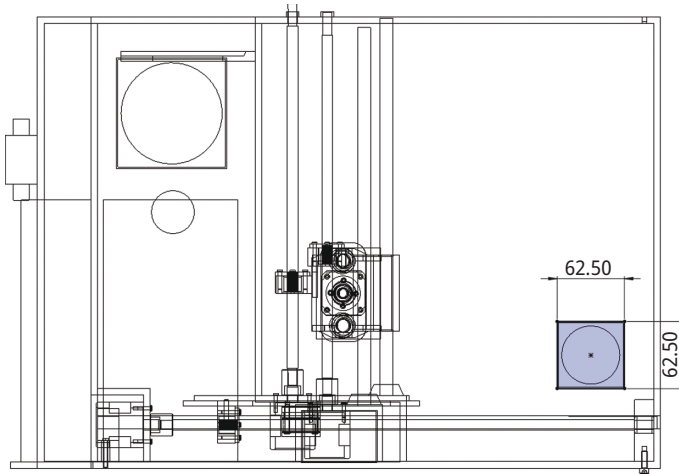


Fig. 6.5: Inlet geometry.

The air inlet is square in geometry as shown in Fig. 6.5; therefore, an equivalent diameter for the calculation of Re needs to be found [30].

$$\text{Side of the inlet} = 62.5 \text{ mm} = 0.0625 \text{ m}$$

$$\text{Perimeter of inlet} = 4 \times 0.0625 \text{ m}$$

$$\text{Area of the inlet} = 0.0625 \text{ m} \times 0.0625 \text{ m}$$

$$d_{eq} = (4 \times 0.0625 \times 0.0625) / 4 \times 0.0625 = 0.0625 \text{ m (mention w.r.t our machine)}$$

$$Re = (0.9459 \times 1.2 \times 0.0625) / 2.173 \times 10^{-5}$$

$$Re = 3,264.72$$

Since $2,000 < Re < 4,000$, the flow regime has been a hybrid of laminar and turbulent.

6.4.4 Boundary conditions

The boundary conditions used are as mentioned in Tab. 6.2 and Fig. 6.6. Although the boundary conditions for both configurations are identical, their positioning differs.

Tab. 6.2: Boundary conditions for the analysis.

Boundary condition	Value
Inlet condition	Constant mass flow rate
Inlet velocity (m/s)	1.2 m/s
Inlet fluid temperature (K)	373.15 K
Flow model	Laminar and turbulent
Turbulent intensity	1%
Turbulent length (m)	0.004 m
Outlet condition	Atmospheric pressure
Wall boundary condition	No-slip wall boundary
Wall temperature (K)	373.15 K

6.5 Results and discussion

Two different configurations for a medical-grade 3D printing machine were developed for our study. The air flow inside the chamber and the heat transfer were studied.

Now, the Re was a primary condition for determining the flow type within the printer casing. The Re was established as an equation goal, following the same parameters as eq. (6.1). Velocity fluctuations were also visualized using flow trajectories.

The Re fluctuated continuously between 1,800 and 2,500 for the first configuration, indicating a desirable laminar flow regime.

For the second configuration, the analysis showed that the Re peaked at around 3,900 before averaging down to approximately 900, which is generally a good indica-

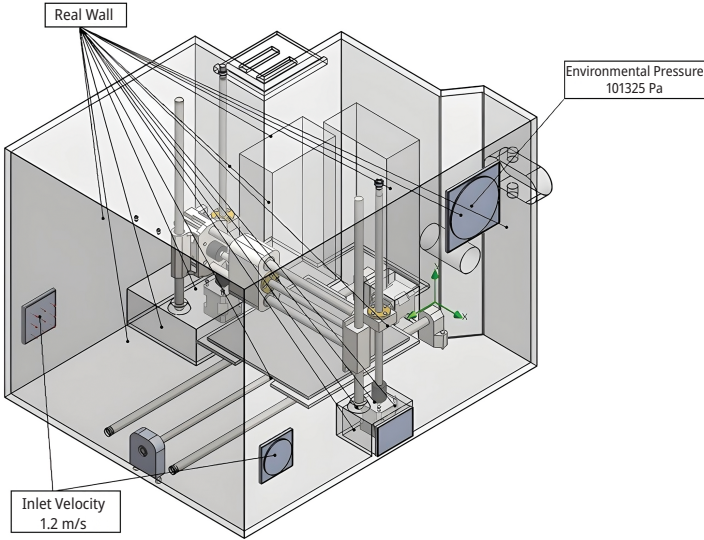


Fig. 6.6: Boundary conditions callout.

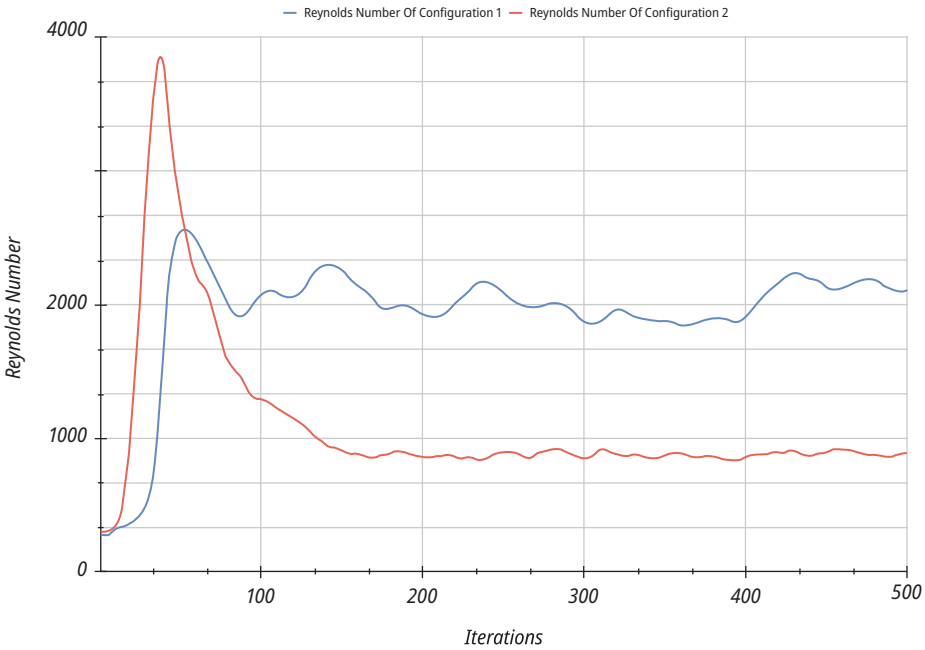


Fig. 6.7: Comparison of Reynolds number of configurations 1 and 2.

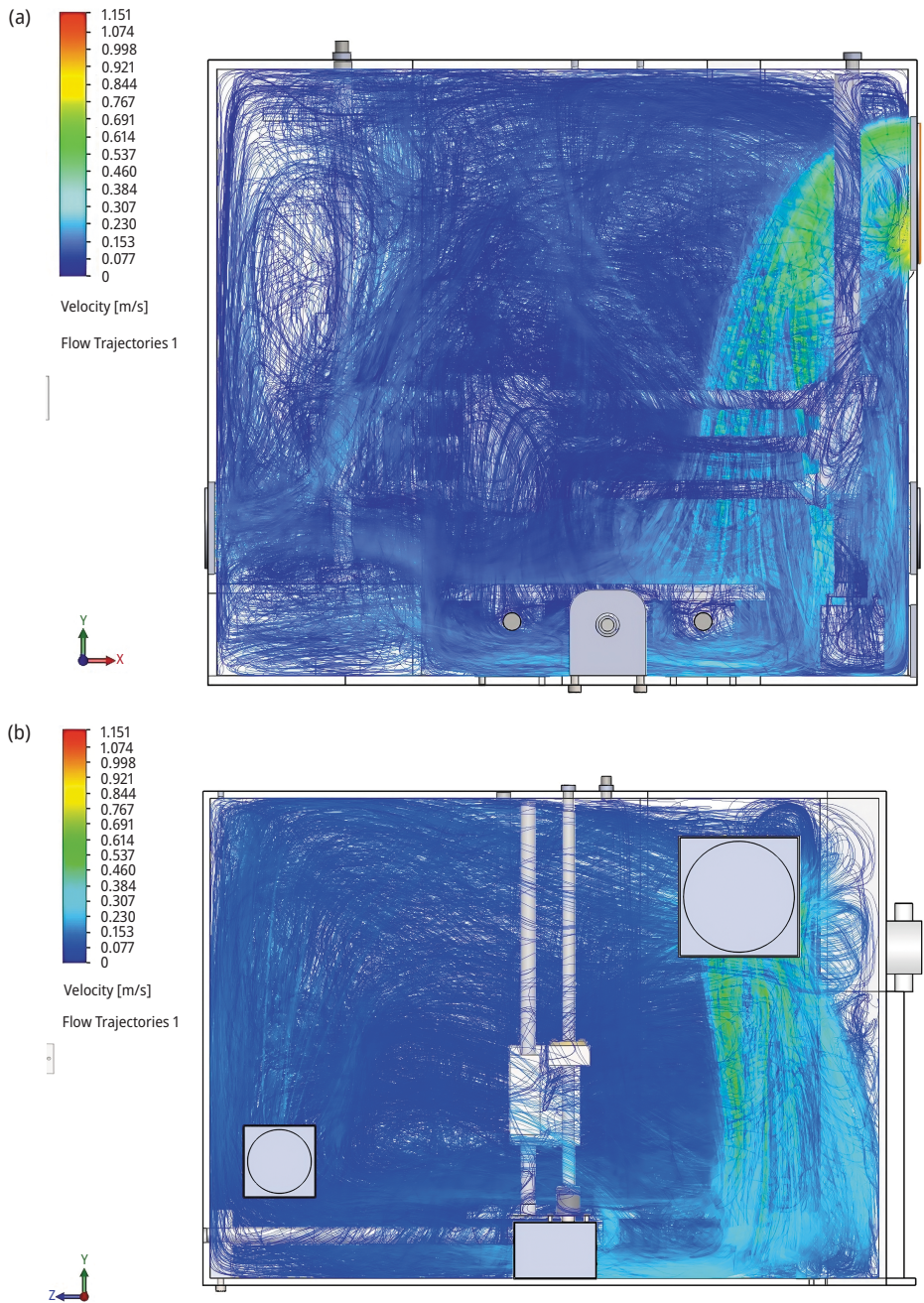


Fig. 6.8: Velocity fluctuations: (a) front view; (b) right view; (c) top view; and (d) isometric view.

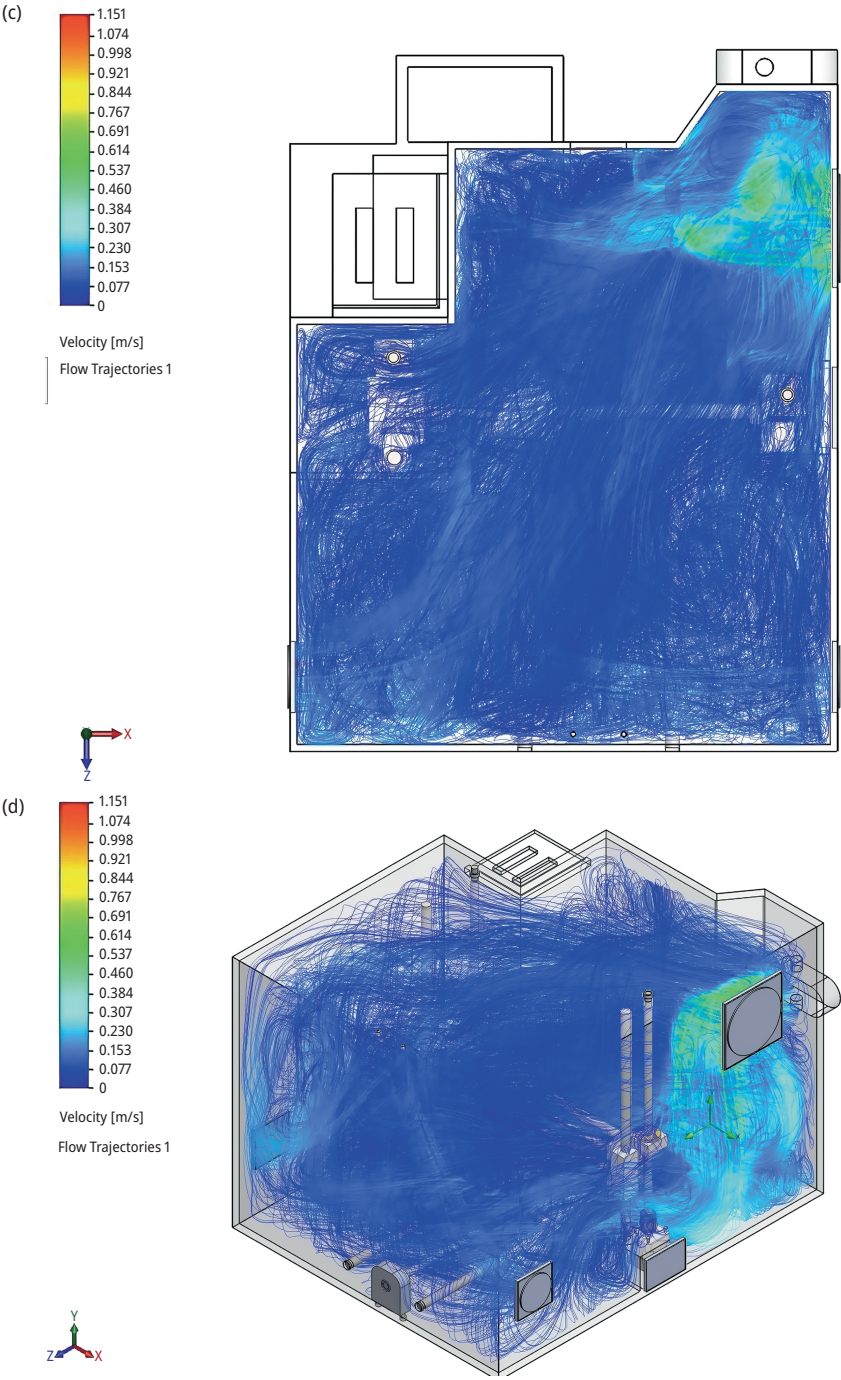


Fig. 6.8 (continued)

tion of a laminar flow regime, except for the initial peak, which could cause air swirls within the casing. A comparison of both configurations, based on the Re , is provided in Fig. 6.7, while the velocity fluctuations from the front, right, top, and isometric views are displayed in Fig. 6.8(a)–(d), respectively. The flow trajectory illustrates how the inlet and outlet positions can alter fluid cell interactions with solid bodies and impact the formation of swirls and eddies.

For obtaining the desired temperature inside the printing machine chamber, heating elements in the form of hot fan blowers were used. The walls of the casing were covered with insulating material to entrap the heat energy in the system. The problem was simplified by making several assumptions, including neglecting heat conduction through solids and heat generation inside the system. The two design configurations had specific boundary conditions and an airflow medium. Simulation results showed that the minimum and maximum temperatures inside the printer casing were within the required range for both configurations. Additionally, it was observed that the temperature inside the printer casing was majorly based on the inlet air heat and quality of insulation provided on the printer walls than on the configuration of the inlet and outlet entities.

The temperature profile inside the casing is shown in Figs. 6.9 and 6.10 for the first and second configurations, respectively. For the first configuration, the velocity fluctuations are shown in Fig. 6.11(a)–(d) from front, right, top, and isometric angles. Figs. 6.11 and 6.12(a)–(d) depict velocity variations for the second configuration from the same front, right, top, and isometric viewing angles.

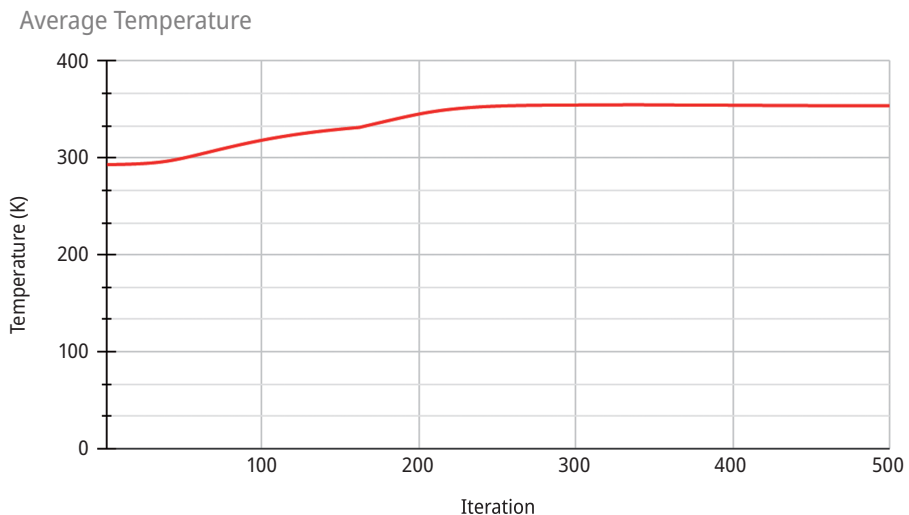


Fig. 6.9: Temperature profile inside casing for configuration one.

Average Temperature of configuration 2

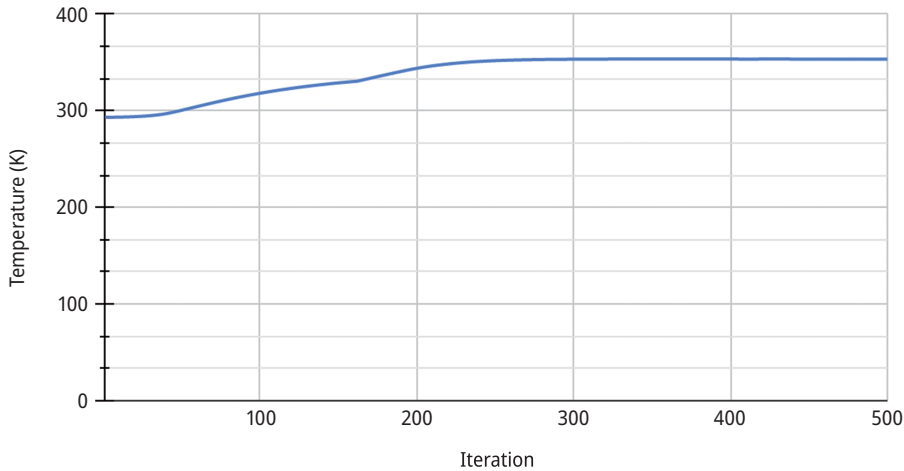


Fig. 6.10: Temperature profile inside casing for configuration two.

The temperature profile inside the printer casing for both configurations remained generally the same and similar in profile. Therefore, it can be concluded that the temperature inside the printer casing is much more dependent on the inlet air temperature and the quality of insulation provided on the printer walls rather than on the configuration of the inlet and outlet entities.

6.6 Conclusion

The purpose of this study was to employ CFD to investigate the flow type inside a medical-grade 3D printer enclosure, focusing on achieving laminar flow and optimizing heat transfer. The primary objective was to ensure smooth fluid flow with minimal eddy formation, as well as maintaining the desired temperature inside the printer casing during the printing of PEEK implants.

The study involved various analyses to study the effects of inlet and outlet design modifications on maintaining a smooth, stable fluid flow with a low Reynolds number (Re). Additionally, the internal geometry of the printer components was optimized to enhance aerodynamic performance and heat transfer.

SolidWorks 2018 Flow Simulation software was utilized to perform the simulations, generating a total of 6,221,440 fluid cells, with 1,997,325 cells interacting with the solid components. The Reynolds number for different configurations ranged from 1800 to 2500 in the first configuration and varied between 950 and 3,900 in the second

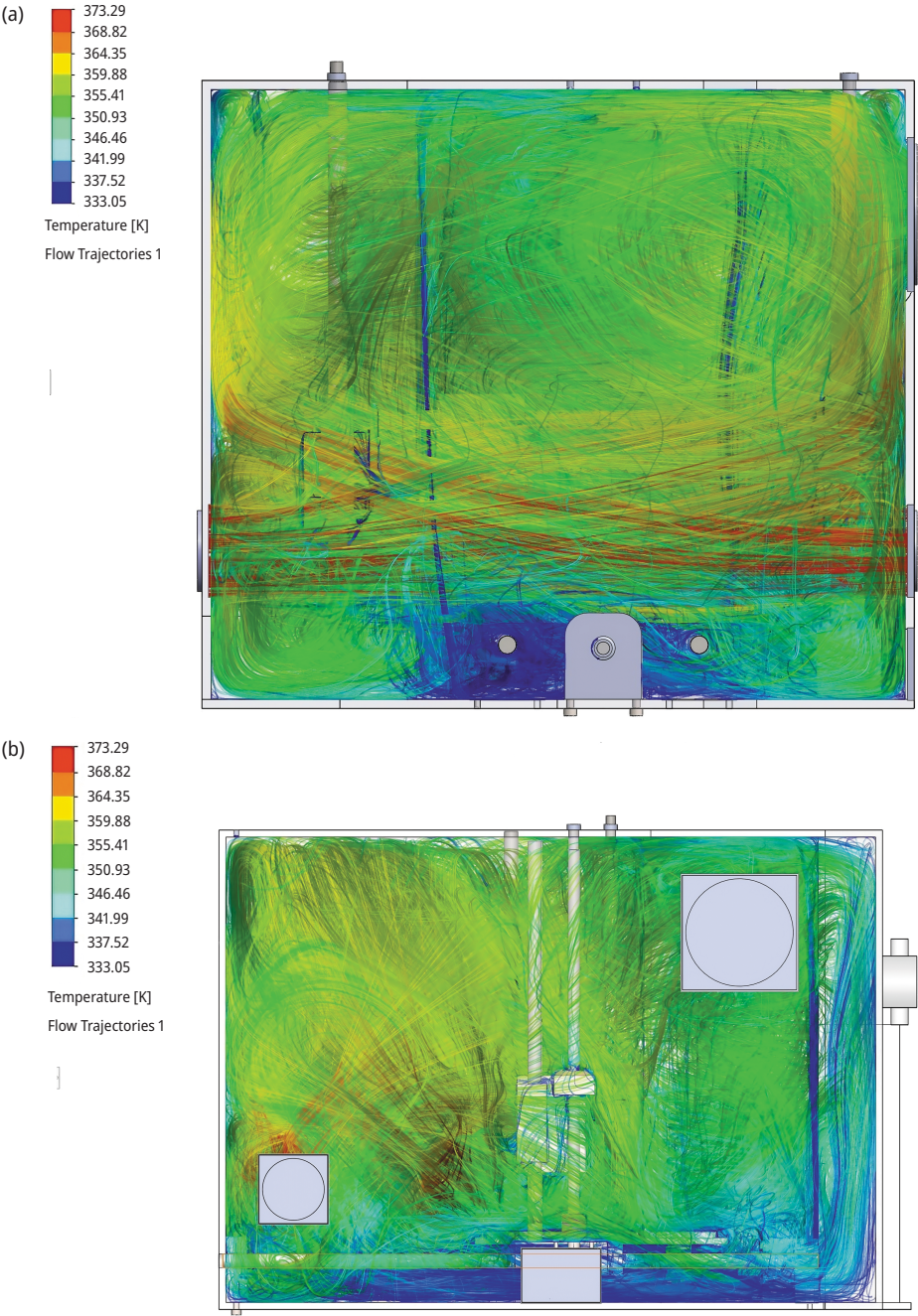


Fig. 6.11: Temperature fluctuations: (a) front view of configuration 1; (b) side view of configuration 1; (c) top view of configuration 1; and (d) isometric view of configuration 1.

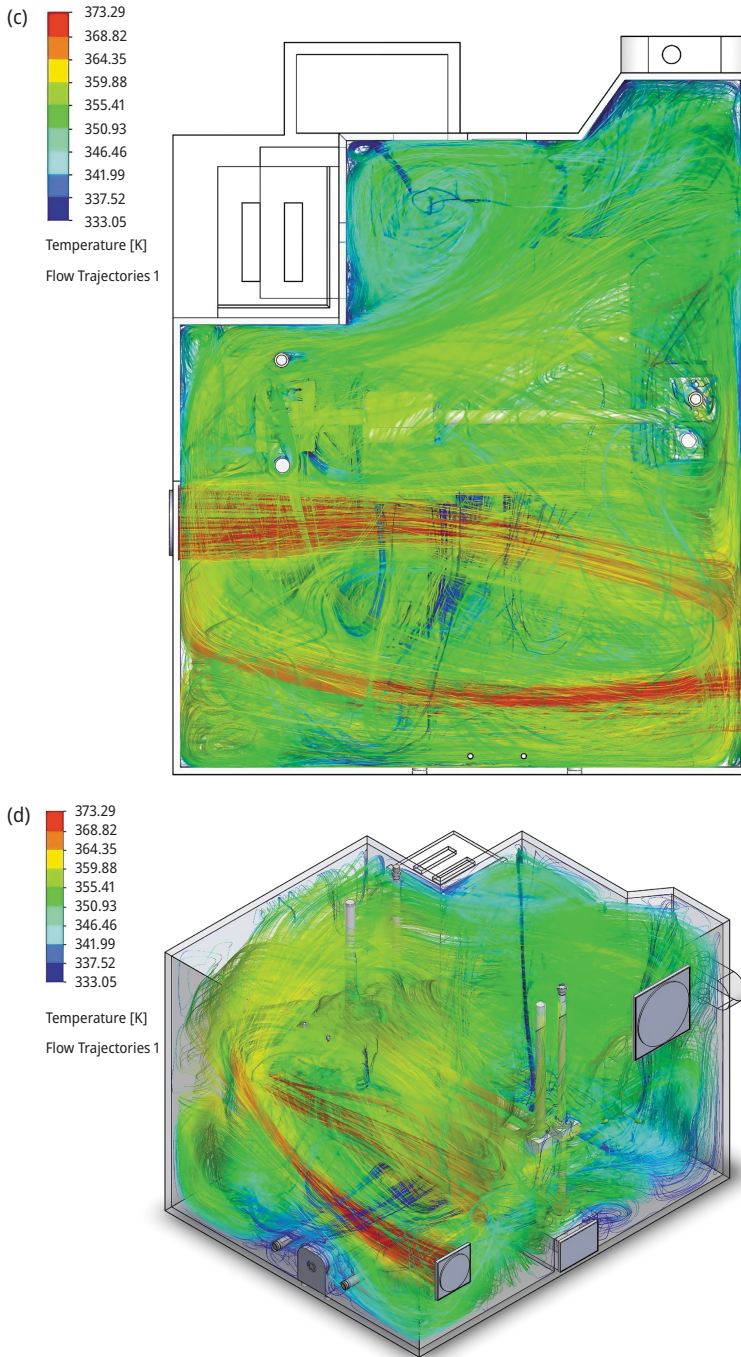


Fig. 6.11 (continued)

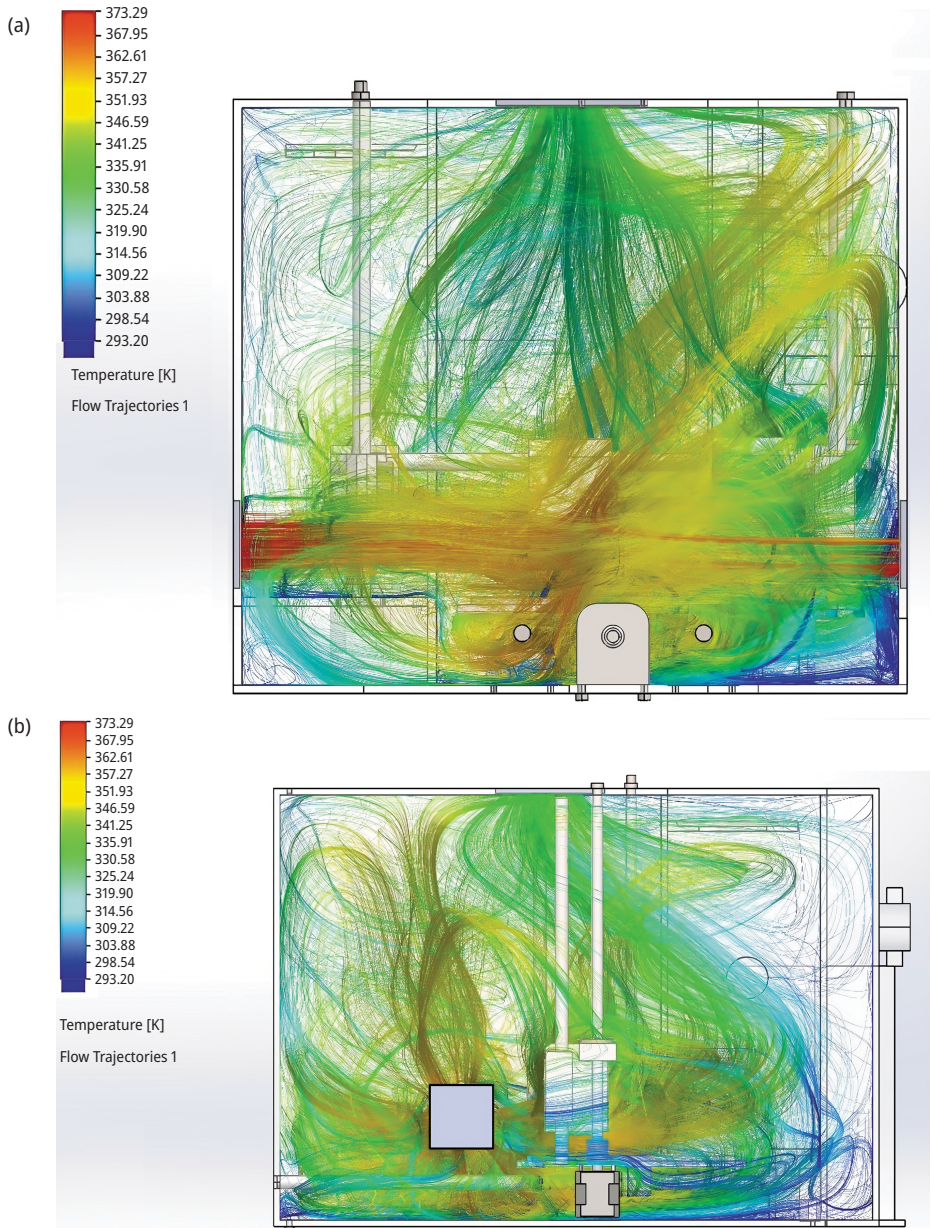


Fig. 6.12: Temperature fluctuations: (a) front view of configuration 2; (b) side view of configuration 2; (c) top view of configuration 2; (d) isometric view of configuration 2.

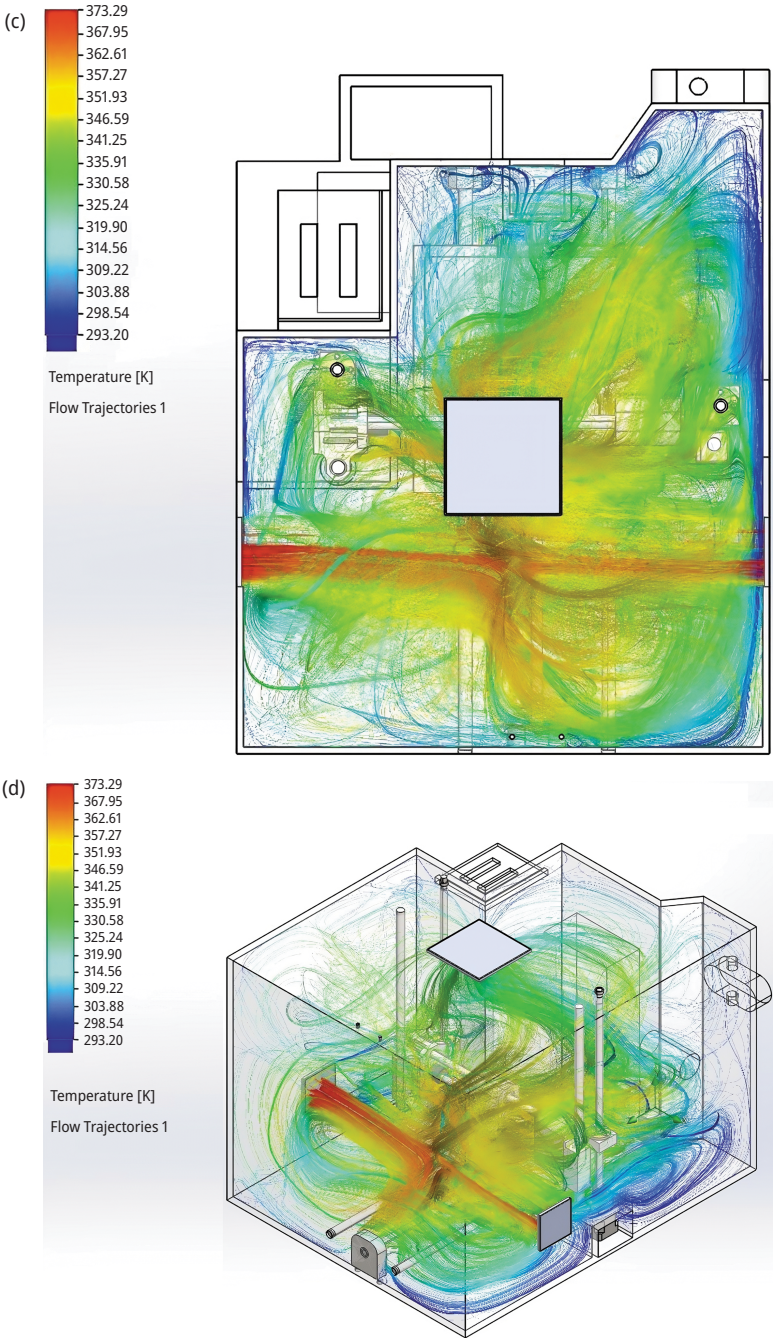


Fig. 6.12 (continued)

configuration. Flow trajectories were examined to visualize velocity fluctuations and identify areas prone to eddy formation.

The simulation results demonstrated that both configurations were able to achieve laminar flow within the 3D printer, thereby ensuring a sterile environment and maintaining the desired temperature for printing PEEK implants. The findings indicated the effectiveness of design modifications and temperature adjustments inside the chamber for regulating airflow and optimizing heat transfer.

Moreover, the research emphasized the importance of material selection for printer components, regular maintenance, and cleaning of the printer chamber to prevent contamination. Advanced monitoring systems for real-time tracking of environmental conditions within the printer chamber are recommended to ensure sterility throughout the printing process.

The successful design of the medical-grade 3D printing machine configurations, coupled with the simulation results, provided valuable insights for further development and improvement of medical-grade 3D printing machines for PEEK implant production. This research serves as a foundation for the construction of a practical medical-grade 3D printer, followed by experimental validation and optimization of the proposed designs in real-world settings.

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Saurabh Tege and Parveen Kumar

7 Review of 4D printing and materials enabling Industry 4.0 for implementation in manufacturing: an Indian context

Abstract: This research chapter aims to conduct a comprehensive review of 4D printing technology and its integration with Industry 4.0 in the context of Indian manufacturing. The chapter discusses the benefits and challenges of implementing 4D printing in the manufacturing sector in India, highlighting the critical role of materials science and engineering in enabling this technology. The chapter also explores the ethical, social, and environmental implications of using 4D printing in Indian manufacturing and identifies key success factors and best practices for scaling up production. The article's final remarks highlight the potential future opportunities and areas of study for 4D printing and materials science as they relate to Industry 4.0 in the Indian manufacturing industry.

Keywords: 4D printing, Industry 4.0, manufacturing sector, environmental implications

7.1 Introduction

Industry 4.0 is a new paradigm in the manufacturing sector, emphasizing the use of advanced technologies, data analytics, and automation. One of the key enablers of Industry 4.0 is 4D printing, a new technology that allows for the creation of self-assembling and shape-changing objects. Nevertheless, there are various obstacles that hinder the adoption of Industry 4.0 and 4D printing technologies in the manufacturing industry of India. The objective of this research chapter is to perform an extensive examination of 4D printing and the materials that facilitate Industry 4.0, with the aim of implementing them in manufacturing within the Indian setting.

7.1.1 Background and overview

Industry 4.0 is a new phase of industrial revolution that focuses on the integration of digital technologies in manufacturing processes. It aims to create a smart and connected factory that can operate autonomously, optimize production processes, and

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minimize human intervention. The integration of 4D printing in Industry 4.0 can lead to significant advancements in manufacturing, where the printed materials can transform their shape, function, and properties in response to external stimuli such as heat, light, and moisture. This technology has the potential to revolutionize the way products are designed, manufactured, and delivered, leading to more efficient and sustainable manufacturing processes.

However, the implementation of 4D printing in manufacturing comes with its own set of challenges, especially in the Indian context. India is an emerging economy that is striving to become a global manufacturing hub. The Indian manufacturing industry is facing several challenges such as inadequate infrastructure, lack of skilled labor, and low adoption of advanced technologies. In this context, this research chapter aims to review the potential of 4D printing and its materials in enabling Industry 4.0 for implementation in the Indian manufacturing industry. The chapter will provide an overview of the technology and materials used in 4D printing, discuss the implementation of 4D printing in Industry 4.0, present case studies on 4D printing in manufacturing, and analyze the challenges and opportunities for its implementation in the Indian manufacturing industry. Finally, the chapter will provide recommendations for the Indian manufacturing industry to successfully adopt 4D printing in their manufacturing processes.

7.1.2 Problem statement

The research chapter aims to review the concept of 4D printing and the materials that enable Industry 4.0 for implementation in manufacturing in the context of India. The chapter seeks to explore the potential of 4D printing technology and the materials used in this process to enhance the capabilities of the manufacturing industry in India. The study intends to examine the current state of 4D printing technology and materials, their advantages, and limitations, and how they can be applied in the Indian manufacturing industry. The research also aims to evaluate the challenges faced by the Indian manufacturing industry in adopting 4D printing and materials enabling Industry 4.0 and recommend strategies for overcoming these challenges. Overall, the chapter seeks to contribute to the existing literature on the application of 4D printing and materials in manufacturing and provide insights into their potential for the Indian context.

7.1.3 Research objectives

- To understand the concept of Industry 4.0 and its implementation in the Indian manufacturing sector.

- To review the state-of-the-art in 4D printing technology and its applications in the manufacturing sector.
- To identify the key challenges and opportunities for implementing 4D printing in the Indian manufacturing sector.
- The objective is to investigate how materials can facilitate 4D printing and Industry 4.0 within the specific context of India.
- The aim is to propose suggestions for effectively integrating 4D printing and Industry 4.0 into the manufacturing industry of India.

7.1.4 Scope and significance

The scope of the research chapter is to explore the concept of 4D printing and the materials that enable Industry 4.0 for implementation in manufacturing in the context of India. The study intends to examine the current state of 4D printing technology and materials, their advantages, and limitations, and how they can be applied in the Indian manufacturing industry. The research also aims to evaluate the challenges faced by the Indian manufacturing industry in adopting 4D printing and materials enabling Industry 4.0 and recommend strategies for overcoming these challenges.

The significance of this research chapter lies in its potential to contribute to the existing literature on the application of 4D printing and materials in manufacturing, particularly in the Indian context. The study can help manufacturing firms in India to understand the potential benefits of 4D printing and materials enabling Industry 4.0 and the challenges associated with their adoption. The research findings can also assist policymakers in developing appropriate strategies for promoting the adoption of 4D printing and materials in the Indian manufacturing industry, which can enhance the country's manufacturing capabilities and competitiveness in the global market. Additionally, the study can serve as a valuable resource for researchers and scholars interested in the field of 4D printing and materials enabling Industry 4.0 in manufacturing.

7.1.5 Research methodology

The research methodology of this chapter involves a comprehensive literature review and qualitative analysis of the data gathered.

The literature review will involve gathering relevant articles, books, and reports on the topic of 4D printing and materials enabling Industry 4.0 in manufacturing, with a focus on the Indian context. The review will include studies on the current state of 4D printing technology and the materials used in the process, the advantages and limitations of the technology, and its potential applications in the Indian manufacturing industry.

The qualitative analysis will involve identifying key themes and patterns in the literature and analyzing them to draw conclusions and make recommendations. The research will also involve collecting primary data through interviews with experts in the field, including manufacturing professionals, researchers, and policymakers.

The data collected through the literature review and interviews will be analyzed using a thematic analysis approach. The analysis will involve identifying patterns and themes in the data, comparing and contrasting them to draw conclusions, and making recommendations based on the findings.

The research methodology for this chapter will also involve a critical review of the limitations of the research, including potential biases and limitations of the data collected. The study will provide a clear and concise methodology that can be replicated by future researchers in the field.

7.2 Literature review

7.2.1 Introduction to 4D printing

Imagine a world where objects could transform and adapt on their own, without the need for human intervention. This may sound like science fiction, but it is becoming a reality with the emergence of 4D printing.

4D printing builds upon the foundation of 3D printing but takes it to the next level by allowing objects to self-transform over time. This means that 4D printed objects can change their shape, size, and even function based on their environment or an external stimulus, such as heat or light. In other words, 4D printing adds the dimension of time to the printed objects, making them responsive and dynamic.

The possibilities of 4D printing are limitless, with potential applications in various fields, including medicine, aerospace, construction, and fashion. For example, 4D printed medical implants could transform and adapt to the patient's anatomy over time, while 4D printed structures could self-repair and adapt to changing environmental conditions.

The secret behind 4D printing lies in the use of smart materials that have the ability to change their properties in response to external stimuli. These materials, such as shape-memory polymers (SMPs) and hydrogels, are deposited using a 3D printer and then activated to transform or self-assemble using a trigger.

As 4D printing continues to evolve, it has the potential to revolutionize the manufacturing industry by enabling the creation of intelligent, self-transforming structures. This chapter aims to review the current state of 4D printing technology and materials and explore their potential for implementation in the Indian manufacturing industry.

7.2.1.1 Definition of 4D printing

4D printing can be defined as an advanced manufacturing technology that builds on the principles of 3D printing but allows objects to self-transform or self-assemble over time with the help of external stimuli. In other words, 4D printing adds the fourth dimension of time to 3D printing, enabling the printed objects to change their shape, function, and even color after they have been printed.

The process of 4D printing involves using smart materials, such as SMPs and hydrogels that can change their properties in response to external stimuli such as heat or water. These materials are deposited layer by layer using a 3D printer and then activated to self-assemble or change their shape using a trigger.

The potential applications of 4D printing are vast, ranging from aerospace and medicine to construction and fashion. For instance, 4D printed medical implants could adapt to the patient's anatomy over time, while 4D printed buildings could self-transform to withstand extreme weather conditions.

Overall, 4D printing represents a major breakthrough in the field of advanced manufacturing, with the potential to revolutionize the way we design and manufacture objects in the future.

7.2.1.2 Brief history of 4D printing

The concept of 4D printing was first introduced by Skylar Tibbits in 2013, a researcher at MIT's Self-Assembly Lab. Tibbits envisioned 4D printing as a way to create objects that could adapt to their environment, self-repair, and evolve over time.

The first 4D printed objects were created using a technique called multimaterial 3D printing, which allowed for the deposition of multiple materials with different properties in a single print. This technique enabled the creation of 4D printed objects with complex shapes and functions.

Since then, 4D printing has gained significant attention from researchers and industries around the world. In 2016, researchers at Singapore's Nanyang Technological University developed a 4D printing method that used cellulose fibers to create objects that could transform into different shapes in response to humidity.

In 2017, a team of researchers from the Georgia Institute of Technology developed a 4D printing method that used SMPs to create objects that could change their shape in response to temperature.

More recently, researchers have been exploring the use of novel materials, such as hydrogels, which can change their shape and properties in response to various stimuli, including temperature, light, and pH. According to Kumar et al. [1], additive manufacturing has advanced significantly, incorporating artificial intelligence (AI), nature-inspired approaches, and biomanufacturing techniques.

In a study by Kumar et al. [2], the integration of reverse engineering with additive manufacturing was explored, highlighting its potential applications and benefits within the field. Kumar et al. [3] discussed printing file formats for additive manufacturing technologies which shed light on the importance of compatible file formats for successful implementation. Materials processed by additive manufacturing techniques were the focus of research by Kumar, Kumar, Mittal, and Gambhir [4], emphasizing the wide range of materials suitable for additive manufacturing processes.

Preprocessing and post-processing methods in additive manufacturing were discussed, highlighting their significance in achieving high-quality printed products [5]. Kumar et al. [6] present a comprehensive resource for forecasting the future of Industry 4.0. Kumar et al. [7] conducted a state-of-the-art review on smart manufacturing and Industry 4.0, providing insights into the latest advancements and trends in the field. Ajay et al. [8] offer a comprehensive exploration of sustainable materials, including their modeling, characterization, and optimization. In a study by Sehrawat et al. [9, 10] the expanding domains of 3D printing in orthodontics were discussed, highlighting its relevance and potential applications in the specialty and also conducted a study on 3D scanning technologies and scanners in orthodontics, providing insights into their usage and benefits within the field. Bhardwaj et al. [11] explored the current trends of additive manufacturing application in the oral healthcare system, emphasizing its potential to revolutionize dental practices.

Li, Dong, and Wang [12] review the current state of 4D printing in hierarchical structures for energy applications. They discuss the potential benefits of 4D printing, such as improved mechanical properties, multifunctionality, and energy efficiency. Shemelya and Esposito [13] present an overview of 4D printing in the industrial sector, including its applications in product design, manufacturing, and supply chain management. Ma, Chen, and Zhang [14] present a thorough evaluation of the materials, structures, and applications involved in 4D printing. They discuss several kinds of stimuli-responsive materials like shape-memory alloys (SMAs), hydrogels, and liquid crystal elastomers (LCEs) and explore how they can be utilized in different fields such as soft robotics, biomedical devices, and energy harvesting. Overall, their review provides a comprehensive understanding of the current state of 4D printing technology. Lin and Chen [15] present the concept of intelligent 4D printing technology and its application in Industry 4.0. They describe how 4D printing can be integrated with AI, the Internet of things (IoT), and big data analytics to enable real-time manufacturing, customization, and automation.

Ahmed et al. [16] review the role of 4D printing in Industry 4.0. They discuss how 4D printing can improve manufacturing efficiency, reduce waste, and enable customization and personalization of products. Li et al. [17] review the application of 4D printing in Industry 4.0, focusing on its potential to transform the manufacturing process from a linear to a circular model.

Zheng and Chen [18] provide an overview of the latest progress in 4D printing technology and its applications in Industry 4.0. They discuss the challenges and opportuni-

ties of 4D printing, including the need for more advanced materials, design tools, and manufacturing processes. Zhang et al. [19] review the 4D printing technology and its application in Industry 4.0. They describe the different types of stimuli-responsive materials and their use in various applications, including aerospace, medicine, and construction. Sun et al. [20] review the principles, methods, and applications of 4D printing of multimaterials. They discuss how the integration of different materials can enable the creation of complex and multifunctional structures with improved performance.

Hu et al. [21] provide a review of 4D printing technology in aerospace. They describe the potential benefits of 4D printing in aerospace, including reduced weight, increased strength, and improved functionality. Jin et al. [22] review the progress of 4D printing technology and its application in engineering construction. They discuss how 4D printing can enable the creation of complex and customized structures with reduced waste and increased efficiency.

Jiao et al. [23] conducted a review on the various ways that 4D printing technology can be utilized in the construction sector. The authors explore the potential applications of this technology and its impact on the construction industry. They discuss how 4D printing can enable the creation of complex and customized structures with reduced waste and increased efficiency. According to Qiu et al. [24], the current state and future direction of 4D printing technology in construction is under review. The article explores the advantages that 4D printing could bring to the industry, such as decreased material waste, enhanced productivity, and better quality.

Wu et al. [25–31] provide an overview of the current state of 4D printing technology, discussing its potential applications in the construction industry. They explain that 4D printing can help to overcome some of the challenges in the construction industry, such as the need for complex shapes and the use of sustainable materials. The chapter also describes various applications of 4D printing in different fields, such as aerospace, biomedicine, and construction. The authors conclude that 4D printing has the potential to revolutionize manufacturing and open up new avenues for design and production.

Wang et al. [32] presented a thorough summary of the current state of 4D printing technology and its utilization in the creation of smart materials. They discussed the challenges and opportunities in the development of this technology and provided insights into the future prospects of 4D printing. The authors emphasized the importance of understanding the fundamental principles of 4D printing, including material selection, design, printing techniques, and post-processing methods, to achieve the desired functionality of smart materials.

In their review article, Han et al. [33] discussed the recent progress and future direction of 4D printing technology. They highlighted the key factors that influence the performance of 4D printed materials, such as material properties, printing parameters, and environmental conditions. The writers gave a summary of the diverse categories of materials that can respond to stimuli and are utilized in 4D printing, along with their possible applications in different domains.

Thakur and Kessler [34] investigated the capability of 4D printing technology to contribute to the development of healthcare systems that are both sustainable and intelligent. They discussed the unique features of 4D printed biomaterials, such as their ability to respond to various stimuli and adapt to different environments, and their potential applications in tissue engineering, drug delivery, and medical devices. Leng and Lan [35] provided an overview of the utilization of 4D printing technology in the field of textiles and garments. Their article examined the diverse range of responsive materials employed in 4D printing, including SMAs, hydrogels, and polymers, and explored their prospective applications in smart wearables and textile devices. The authors also highlighted the challenges and opportunities in the development of 4D printed textiles and clothing, such as design, material selection, and manufacturing processes.

Wang et al. [36] presented a summary of the advancements and future potential of 4D printing technology in the realm of polymer materials. The authors examined the varying kinds of polymers that respond to different stimuli used in 4D printing and their prospective applications across multiple industries, including aerospace, automotive, and biomedical engineering. The chapter also drew attention to the obstacles and chances for improvement in 4D printing technology for polymer materials, including synthesizing materials, printing methods, and methods for post-processing.

In their study published in 2017, Almpanis and Kyriakopoulos [37] delved into the potential uses of 4D printing technology in the fashion sector. They examined the distinct characteristics of 4D printed materials, including their capacity to transform their shape and hue as time progresses, and how they could be utilized in fashion design, textile production, and personalized product creation. The authors also pinpointed the obstacles and possibilities associated with integrating 4D printing technology into the fashion industry, which include design, material selection, and manufacturing processes.

Romero and Navarro [38] conducted a review of the ways in which 4D printing technology can be utilized within the textile industry. They explored various categories of materials that respond to different types of stimuli and their potential uses in the creation of smart textiles, medical textiles, and fashion. The authors also highlighted the challenges and opportunities in the development of 4D printed textiles, such as material selection, printing techniques, and postprocessing methods.

Wang and Gao [39] provided a comprehensive review on 4D printing of polymers for biomedical applications. They began by discussing the concept of 4D printing and its advantages over conventional 3D printing. They highlighted the importance of using polymers in 4D printing due to their excellent mechanical properties, biocompatibility, and ease of processing.

Jin et al. [40] conducted an extensive analysis of the advancements made in 4D bioprinting for tissue engineering in recent times. Their review covers a wide range of developments in the field. The authors discussed the importance of 4D bioprinting in creating functional and complex tissue structures that mimic the natural extracellular matrix. They highlighted the advantages of 4D bioprinting over conventional tissue engineering techniques, such as improved cell viability, spatial resolution, and

control over the microenvironment. They also highlighted the importance of bioprinting technologies in achieving precise and controlled cell deposition and tissue formation. The authors discussed various applications of 4D bioprinting, including the development of tissue models for drug screening, personalized medicine, and regenerative medicine. They also discussed the challenges in 4D bioprinting, such as the need for biocompatible materials, scalable production, and regulatory approval. Overall, this review highlighted the potential of 4D bioprinting in tissue engineering and provided insights into the current state of research. Zolfagharian et al. [41] provided a comprehensive review on 4D printing for biomedical applications. The authors began by discussing the concept of 4D printing and its different types of stimuli-responsive materials. They highlighted the importance of 4D printing in biomedical applications, such as the development of smart medical devices, surgical tools, and drug delivery systems.

7.2.1.3 Research gap

One potential research gap in the Indian context could be investigating the feasibility and potential of using 4D printing technology for sustainable and affordable housing construction. Despite the growing interest in 4D printing technology in the construction industry, there has been limited research on its application in low-cost housing construction, particularly in the Indian context where there is a significant demand for affordable and sustainable housing solutions. Therefore, the research can explore the potential of 4D printing technology to create sustainable and affordable housing units in India, including examining the materials and technology required, design possibilities, cost-effectiveness, and environmental impact. This research could provide valuable insights into the potential of 4D printing technology in addressing the housing crisis in India and contribute to the development of sustainable and innovative housing solutions.

7.2.2 Materials used in 4D printing

The materials used in 4D printing are typically smart materials that can change their shape, size, or properties in response to external stimuli, such as heat, light, or moisture. Here are some of the most common materials used in 4D printing:

1. **SMPs:** These are a class of smart polymers that can “remember” their original shape and return to it when triggered by an external stimulus, such as heat. SMPs are often used in medical implants, where they can adapt to the patient’s anatomy over time.
2. **Hydrogels:** These are a type of polymer that can absorb water and change their shape or size in response to external stimuli such as temperature, pH, or light.

Hydrogels are used in various applications, such as drug delivery systems, tissue engineering, and soft robotics.

3. LCEs: These are polymers that can change their shape in response to changes in temperature or light. LCEs are used in various applications, such as soft robotics, sensors, and actuators.
4. SMAs: These are metals that can “remember” their original shape and return to it when triggered by an external stimulus, such as heat. SMAs are used in various applications, such as aerospace, automotive, and medical devices.
5. Composites: These are materials made by combining two or more different materials, such as polymers and nanoparticles, to create new materials with unique properties. Composites can be designed to respond to specific stimuli, such as heat or light, and are used in various applications, such as sensors and actuators.

7.2.2.1 Types of materials used in 4D printing

The materials used in 4D printing can be broadly classified into two categories: active materials and passive materials.

Active materials are those that can change their shape or properties in response to external stimuli, such as heat, light, or moisture. These materials play a critical role in enabling the self-transforming properties of 4D printed objects. Some common examples of active materials used in 4D printing include:

- a) SMPs: These are a type of polymer that can “remember” their original shape and return to it when triggered by an external stimulus, such as heat.
- b) Hydrogels: These are a type of polymer that can absorb water and change their shape or size in response to external stimuli such as temperature, pH, or light.
- c) LCEs: These are polymers that can change their shape in response to changes in temperature or light.
- d) SMAs: These are metals that can “remember” their original shape and return to it when triggered by an external stimulus, such as heat.

Passive materials, on the other hand, do not have self-transforming properties but are used in conjunction with active materials to create 4D printed objects. These materials serve as the support structure or framework for the active materials to perform their self-transforming functions. Some common examples of passive materials used in 4D printing include:

- a) Polymers: These are a broad class of materials that can be used to create support structures for 4D printed objects.
- b) Metals: Metals such as aluminum, titanium, and stainless steel can be used to create structural support for 4D printed objects.
- c) Ceramics: Ceramic materials can be used to create support structures for 4D printed objects, particularly in high-temperature applications.

The choice of materials used in 4D printing depends on the desired properties and functions of the 4D printed objects as well as the specific external stimuli that will trigger their self-transforming behavior.

7.2.2.2 Properties of 4D printing materials

The properties of 4D printing materials can vary depending on the specific type of material used, but they generally have some common characteristics that enable their self-transforming behavior. Here are some of the key properties of 4D printing materials:

1. **Responsiveness to external stimuli:** 4D printing materials have the ability to change their shape or properties in response to specific external stimuli, such as temperature, moisture, or light.
2. **Shape memory:** Some 4D printing materials, such as SMPs and SMAs, have the ability to “remember” their original shape and return to it when triggered by an external stimulus.
3. **Self-assembly:** 4D printing materials can be designed to assemble themselves into specific shapes or structures when triggered by an external stimulus.
4. **Biocompatibility:** Many 4D printing materials, such as hydrogels and SMPs, are biocompatible and can be used in medical applications.
5. **Durability:** 4D printing materials are often designed to be durable and withstand repeated self-transformations.
6. **Tunable properties:** The properties of 4D printing materials can be tuned by adjusting their composition or the external stimulus used to trigger their self-transforming behavior.
7. **Combinatorial properties:** By combining different 4D printing materials, it is possible to create objects with unique combinations of properties, such as stiffness, elasticity, and conductivity.

The properties of 4D printing materials enable them to exhibit self-transforming behavior and hold great potential for a wide range of applications, from aerospace and automotive to healthcare and robotics.

7.3 Industry 4.0 and manufacturing

Industry 4.0, also known as the Fourth Industrial Revolution, refers to the integration of advanced technologies and digitalization into manufacturing processes. The term was first coined in Germany in 2011 and has since gained widespread use across the globe. Industry 4.0 represents a significant shift in manufacturing, as it brings to-

gether physical and digital systems to create smart factories that are more efficient, productive, and responsive to customer needs.

One of the key features of Industry 4.0 is the IoT, which allows for the connection of machines, sensors, and devices to a network. This connectivity enables data to be collected in real time and analyzed to identify inefficiencies and optimize processes. For example, sensors can be used to monitor equipment performance and detect potential issues before they cause downtime, while data analytics can be used to identify patterns and trends that can inform decisions around production planning, inventory management, and quality control.

Another critical component of Industry 4.0 is AI and machine learning, which can be used to automate tasks and improve decision-making. Machine learning algorithms can be trained on large datasets to identify patterns and make predictions, while AI can be used to analyze data and provide insights that would be difficult or impossible for humans to detect. This technology can be used to optimize production processes, reduce waste, and improve product quality.

In addition to IoT and AI, Industry 4.0 also includes other advanced technologies such as robotics, augmented reality, and 3D printing. These technologies can be used to automate tasks and improve efficiency, while also enabling greater customization and flexibility in production.

One of the main benefits of Industry 4.0 is its ability to enable mass customization. With smart factories, it is possible to produce small batches of customized products at the same cost as mass-produced items. This means that manufacturers can respond more quickly to changing customer needs and preferences, which is essential in today's fast-paced market.

However, Industry 4.0 also presents challenges, particularly around workforce development and cybersecurity. As factories become more digitized, the workforce will need to acquire new skills to operate and maintain these technologies. There is also a need for greater cybersecurity measures to protect against the growing threat of cyberattacks.

In conclusion, Industry 4.0 represents a significant transformation in manufacturing, bringing together advanced technologies to create smart factories that are more efficient, flexible, and responsive to customer needs. While there are challenges to overcome, the benefits of Industry 4.0 are clear, and it is likely to continue to revolutionize the manufacturing industry in the years to come.

7.3.1 Industry 4.0 concepts and technologies

Industry 4.0 represents a new era in manufacturing, characterized by the integration of advanced technologies and digitalization into production processes. This integration has given rise to many unique concepts and technologies that are changing the

way manufacturers operate. Here are some of the most notable Industry 4.0 concepts and technologies:

1. **Cyber-physical systems:** Cyber-physical systems (CPS) are systems that combine physical and digital components, such as sensors, actuators, and control systems. These systems are designed to be highly responsive and adaptable, allowing for real-time monitoring and control of production processes. CPS can be used to optimize production efficiency, reduce waste, and improve product quality.
2. **Digital thread:** The digital thread is a concept that refers to the digital representation of a product or process throughout its entire lifecycle. This includes design, manufacturing, testing, and maintenance. The digital thread allows manufacturers to track and optimize every aspect of production from the supply chain to the final product.
3. **Big data analytics:** Big data analytics involves the use of advanced analytics tools to extract insights from large volumes of data. In manufacturing, big data analytics can be used to optimize production processes, identify inefficiencies, and improve product quality. By analyzing data from sensors, machines, and other sources, manufacturers can gain a deeper understanding of their operations and make data-driven decisions.
4. **Cloud computing:** Cloud computing refers to the practice of storing and accessing data and applications over the internet. In manufacturing, cloud computing can be used to store and analyze large volumes of data from sensors and other devices, allowing for real-time monitoring and analysis of production processes. Cloud computing can also enable collaboration between different teams and locations.
5. **Autonomous robots:** Autonomous robots are robots that can perform tasks without human intervention. These robots can be used in manufacturing to perform repetitive tasks, freeing up human workers to focus on more complex or creative tasks. Autonomous robots can also improve efficiency and reduce the risk of accidents.
6. **Advanced materials:** Advanced materials are materials that have been engineered to have specific properties, such as increased strength, flexibility, or conductivity. These materials can be used in manufacturing to create products that are stronger, lighter, and more durable. Advanced materials can also enable new applications, such as the use of 3D printing to create complex parts.
7. **Digital platforms:** Digital platforms are online platforms that enable collaboration and exchange between different stakeholders. In manufacturing, digital platforms can be used to connect suppliers, manufacturers, and customers, enabling real-time collaboration and communication. Digital platforms can also provide data analytics and other tools to improve efficiency and optimize production processes.

7.3.2 Impact of Industry 4.0 on manufacturing

Industry 4.0 has the potential to transform the way manufacturing is done, with its advanced technologies and intelligent systems. The impact of Industry 4.0 on manufacturing is profound and far-reaching, touching on all aspects of the production process, from design and planning to production, delivery, and even after-sales service. Here are some of the ways in which Industry 4.0 is impacting manufacturing:

- 1) **Increased efficiency:** Industry 4.0 technologies such as automation, robotics, and AI are enabling manufacturers to increase efficiency by optimizing production processes and reducing waste.
- 2) **Improved quality:** With the use of sensors, data analytics, and machine learning algorithms, manufacturers can monitor and control the quality of their products at every stage of production, leading to higher quality products and fewer defects.
- 3) **Greater flexibility:** Industry 4.0 technologies allow for greater flexibility in manufacturing processes, enabling manufacturers to produce smaller batches of customized products more quickly and efficiently.
- 4) **Enhanced safety:** Advanced safety systems and sensors can be integrated into production processes, reducing the risk of accidents and injuries in the workplace.
- 5) **Increased innovation:** Industry 4.0 technologies are opening up new possibilities for innovation and product development, enabling manufacturers to create new products and services that were previously impossible.
- 6) **Improved supply chain management:** With the use of digital technologies such as the IoT, manufacturers can gain greater visibility and control over their supply chains, improving logistics, inventory management, and delivery times.
- 7) **Enhanced customer experience:** By leveraging Industry 4.0 technologies such as predictive analytics and AI, manufacturers can gain a better understanding of customer needs and preferences, enabling them to deliver more personalized and engaging customer experiences.

7.4 Implementation of 4D printing in manufacturing

4D printing is a relatively new technology that builds on the principles of 3D printing. The key difference between 4D printing and 3D printing is that 4D printing allows printed objects to change their shape over time in response to certain stimuli, such as heat, moisture, or light. This capability makes 4D printing attractive for manufacturing applications where products with complex geometries or functional properties are required.

The implementation of 4D printing in manufacturing involves several steps:

- **Design:** The first step in implementing 4D printing in manufacturing is to design a 3D object that has the desired shape and properties. This involves considering the

material properties, the intended application, and the stimuli that will trigger the shape change.

- **Material selection:** Once the design is complete, the appropriate materials for 4D printing must be selected. These materials must be able to respond to the desired stimuli and be compatible with the 3D printing process.
- **Printing:** The 3D printing process is then used to fabricate the object. This process involves depositing layers of the selected material onto a substrate in a controlled manner to build up the desired shape.
- **Post-processing:** After the 3D printing process is complete, the object must undergo post-processing to activate the shape-changing mechanism. This may involve applying heat, moisture, or light to the printed object to trigger the shape change.
- **Testing and validation:** Finally, the printed object must undergo testing and validation to ensure that it meets the required performance criteria. This may involve testing the shape-changing mechanism, mechanical properties, and durability of the object.

7.4.1 Benefits of 4D printing in manufacturing

- 1) **Design flexibility:** 4D printing allows for the creation of complex and dynamic geometries that would be difficult or impossible to produce using traditional manufacturing methods. This means designers can create more complex and functional objects, leading to more innovation in product design.
- 2) **Reduced material waste:** 4D printing can use materials more efficiently and reduce waste by creating self-assembling structures that require fewer parts and less material.
- 3) **Customization:** 4D printing can be used to create customized products, like medical implants or eyewear, which can be tailored to fit an individual's specific needs or preferences.
- 4) **Reduced assembly time:** The use of 4D printing can reduce the time required for assembly and finishing of parts by creating objects that self-assemble or self-transform.
- 5) **Reduced manufacturing costs:** 4D printing can reduce the cost of manufacturing by reducing the number of parts required, minimizing assembly time and labor costs, and using materials more efficiently.
- 6) **Enhanced product performance:** 4D printed objects can have enhanced mechanical, electrical, or optical properties that can improve product performance and functionality.
- 7) **Self-repairing capabilities:** 4D printed objects can have the ability to self-repair or self-heal, which can increase product durability and longevity.

- 8) Environmental sustainability: By reducing material waste and using materials more efficiently, 4D printing can contribute to more sustainable manufacturing processes that minimize environmental impact.

4D printing has the potential to revolutionize manufacturing by offering more design flexibility, customization, and sustainability, while also reducing costs and improving product performance. However, it is still an emerging technology, and more research and development is needed to fully realize its potential in industrial applications.

7.4.2 Challenges of 4D printing implementation in manufacturing

While 4D printing has the potential to revolutionize manufacturing processes, there are also several challenges associated with its implementation. Here are some of the key challenges:

1. Complexity: 4D printing is a complex technology that requires advanced materials, equipment, and software. This can make it difficult for manufacturers to implement the technology and require significant investments in research and development.
2. Material development: 4D printing requires the development of advanced materials that can change their shape, size, or properties in response to external stimuli. This can be a time-consuming and expensive process, and the materials need to be optimized for specific applications.
3. Limited commercial availability: Commercially available 4D printing equipment and software are still limited, which can make it difficult for manufacturers to implement the technology at scale.
4. Quality control: The dynamic nature of 4D printed objects can make it difficult to ensure consistent quality and performance. This can be a challenge for industries that require high levels of precision and repeatability.
5. Intellectual property issues: The use of 4D printing can raise intellectual property concerns, as it may be difficult to protect designs and prevent unauthorized replication or modification.
6. Safety concerns: The use of advanced materials and complex structures in 4D printing can raise safety concerns related to toxicity, flammability, or other hazards.
7. Regulatory challenges: The use of 4D printing in industries such as healthcare may face regulatory challenges related to safety and efficacy, which can slow down adoption.
8. Printing process optimization: 4D printing is a complex and multistep process that involves printing, curing, and activation of the printed object. Optimizing the printing process and ensuring consistent and reliable performance of the printed objects is a key challenge.

9. Control and programming: To achieve the desired shape-changing behavior, 4D printed objects require precise control and programming of the stimuli that trigger the shape change. Developing effective control algorithms and software tools is a significant challenge.
10. Manufacturing scale-up: While 4D printing has shown promise in research labs, scaling up to industrial-scale manufacturing presents significant challenges. Manufacturing 4D printed objects at scale requires developing efficient and reliable manufacturing processes that can meet the demands of mass production.
11. Cost: 4D printing is currently more expensive than traditional manufacturing methods due to the high cost of materials, equipment, and expertise required. Reducing the cost of 4D printing to make it competitive with other manufacturing techniques is a significant challenge.

7.5 Case studies

7.5.1 Case study 1: 4D printing in aerospace manufacturing

4D printing in aerospace manufacturing comes from a joint project between Airbus and the University of Bristol in the UK. In this project, researchers used 4D printing to create a new type of aircraft wing that can change its shape in response to different flight conditions.

The wing was designed using a combination of 3D printing and embedded SMA wires that can contract or expand in response to changes in temperature. When the wing is heated, the SMA wires contract and cause the wing to bend upward, which can improve lift and reduce drag during flight. When the wing cools down, the SMA wires expand again and return the wing to its original shape.

To manufacture the wing, the researchers used a 3D printer to create a rigid plastic frame, which was then fitted with the SMA wires and covered in a flexible, lightweight skin. The final product was a fully functional aircraft wing that can change its shape and improve aerodynamic performance.

This 4D printed wing has the potential to improve aircraft efficiency and reduce fuel consumption, which is a major concern in the aerospace industry. The use of 4D printing allowed the researchers to create a wing with complex geometries and functional properties that would be difficult or impossible to produce using traditional manufacturing methods.

While this project is still in the research and development stage, it demonstrates the potential for 4D printing to revolutionize aerospace manufacturing by enabling the creation of new and innovative products with enhanced functionality and performance.

7.5.2 Case study 2: 4D printing in medical device manufacturing

One notable case study of 4D printing in medical device manufacturing comes from the Wake Forest Institute for Regenerative Medicine in North Carolina, USA. In this project, researchers used 4D printing to create a new type of vascular graft that can change its shape and function over time in response to changes in the body.

The vascular graft was designed using a combination of 3D printing and smart materials that can change their shape in response to changes in temperature or pH. The researchers printed the vascular graft with two different materials – a rigid, bio-compatible polymer, and an SMP that can expand or contract in response to changes in temperature. The graft was then seeded with human cells and implanted into a rat model to evaluate its performance.

After implantation, the graft expanded and contracted in response to changes in temperature and pressure, adapting to the surrounding tissue and promoting blood flow through the graft. The researchers also observed that the graft integrated well with the surrounding tissue and did not cause any adverse effects.

This 4D printed vascular graft has the potential to revolutionize the field of regenerative medicine by enabling the creation of implantable devices that can adapt to changes in the body and promote tissue regeneration. The use of 4D printing allowed the researchers to create a device with complex geometries and functional properties that would be difficult or impossible to produce using traditional manufacturing methods.

This case study demonstrates the potential for 4D printing to transform medical device manufacturing by enabling the creation of personalized, adaptive devices that can improve patient outcomes and quality of life.

7.5.3 Case study 3: 4D printing in automotive manufacturing

One case study of 4D printing in automotive manufacturing comes from a joint project between BMW and MIT's Self-Assembly Lab in the USA. In this project, researchers used 4D printing to create a new type of car seat that can adjust its shape and comfort level based on the driver's preferences.

The car seat was designed using a combination of 3D printing and smart materials that can change their shape in response to changes in temperature or pressure. The researchers printed the seat with a multimaterial 3D printer that enabled them to incorporate different levels of stiffness and softness throughout the seat. They also embedded sensors in the seat that can detect changes in pressure and temperature.

After printing, the seat was activated using a heat source, which caused the smart materials to expand and contract, adjusting the shape of the seat to fit the driver's body. The sensors also detected changes in pressure and temperature and adjusted the seat accordingly.

This 4D printed car seat has the potential to improve driver comfort and reduce fatigue by providing a personalized seating experience that adapts to the driver's body and preferences. The use of 4D printing allowed the researchers to create a seat with complex geometries and functional properties that would be difficult or impossible to produce using traditional manufacturing methods.

This case study demonstrates the potential for 4D printing to transform automotive manufacturing by enabling the creation of personalized, adaptive products that can improve the user experience and differentiate products from competitors.

7.6 Methodology

7.6.1 Research design

The research design for this chapter will be a literature review with a qualitative approach. The literature review will be conducted by collecting and analyzing relevant academic and industry publications, including research chapters, case studies, and reports. The qualitative approach will allow for the in-depth analysis of the information gathered from the literature review.

The research will be divided into several phases, including:

- a) Identification of relevant literature: A comprehensive search of academic databases, such as Google Scholar, IEEE Xplore, and ScienceDirect, will be conducted to identify relevant literature on 4D printing, materials, and Industry 4.0. The search will be limited to publications from the last five years to ensure the most current and relevant information.
- b) Data collection: The data collected will include information on the definition and history of 4D printing, types of materials used in 4D printing, the benefits and challenges of implementing 4D printing in manufacturing, case studies of 4D printing in different industries, and the challenges and opportunities for implementing 4D printing in the Indian manufacturing industry.
- c) Data analysis: The collected data will be analyzed using a thematic analysis approach. The data will be categorized into themes based on their relevance to the research objectives. The analysis will provide a comprehensive overview of the potential of 4D printing and its materials in enabling Industry 4.0 for implementation in the Indian manufacturing industry.

The research design will be iterative and any new information or findings will be incorporated into the analysis. The qualitative approach will allow for a deep understanding of the implementation of 4D printing in the Indian manufacturing industry and provide recommendations for successful implementation.

7.6.2 Data collection

- a) Define the research questions: Determine what information you need to gather from the surveys and interviews. This will help you create a focused and effective questionnaire.
- b) Determine the sample size and population: Decide on the number of participants you need to reach out to for your survey or interview. You should also define the population you are targeting, which will help you create a representative sample.

Population: The population for this research would be individuals working in the manufacturing industry in India who have knowledge and experience in 4D printing and materials enabling Industry 4.0.

Sample size: The sample size can be determined using a statistical formula based on the desired level of precision, the variability of the population, and the level of confidence required. Assuming a confidence level of 95% and a margin of error of 5%, the estimated sample size can be calculated as follows:

$$n = (Z^2 \times p \times q) / e^2$$

where Z is the standard normal deviate (set at 1.96 for 95% confidence), p the estimated proportion of population with knowledge and experience in 4D printing and materials enabling Industry 4.0 (unknown, but assumed to be 50% for sample size estimation purposes), $q = 1 - p$, and e the desired margin of error (set at 5%).

Using these values, the estimated sample size would be:

$$n = (1.96^2 \times 0.5 \times 0.5) / 0.05^2 = 384.16 \approx 385$$

Therefore, a sample size of 385 individuals working in the manufacturing industry in India with knowledge and experience in 4D printing and materials enabling Industry 4.0 would be sufficient to estimate the population parameters with 95% confidence and a margin of error of 5%.

- c) Create the survey or interview questions: Prepare clear and concise questions shown in Appendix 7.1 that will help you gather the information you need. You can use open-ended and closed-ended questions, depending on the type of information you want to gather.
- d) Pilot test the survey or interview: Before conducting the actual survey or interview, pilot test mentioned in Appendix 7.1 questions with a few participants to ensure that they are clear and effective.
- e) Conduct the survey or interview: Reach out to participants and conduct the survey or interview based on Appendix 7.1. Make sure to follow ethical guidelines and ensure the privacy and confidentiality of participants.
- f) Analyze the data: Once you have gathered the data, analyze it using appropriate statistical methods to draw meaningful conclusions.

- g) Report the findings: Finally, report the findings of your survey or interview in a clear and concise manner, providing relevant data

7.6.3 Data analysis

The current trends and advancements in 4D printing technology (Fig. 7.1) are focused on developing new materials, printing techniques, and design software to create more complex and dynamic structures that can respond to external stimuli. These advancements are closely related to Industry 4.0, which emphasizes the use of digital technologies to create smart and interconnected manufacturing ecosystems. In the context of Indian manufacturing, the adoption of 4D printing can help companies enhance their efficiency, flexibility, and innovation capabilities.

The benefits of implementing 4D printing in the manufacturing sector in India (Fig. 7.2) include reduced production time, waste, and costs as well as the ability to create complex geometries and functional structures. However, the challenges include the high cost of equipment and materials, the need for skilled labor and specialized software, and the lack of standardization and regulation. Compared to other additive manufacturing technologies, such as 3D printing, 4D printing offers the additional advantage of creating self-assembling and self-replicating structures.

Materials science and engineering play a critical role in enabling the implementation of 4D printing in Indian manufacturing (Fig. 7.3). Suitable materials should have the desired mechanical, thermal, and chemical properties as well as temperature, humidity, or light. Key considerations for selecting suitable materials include their biocompatibility, recyclability, and scalability.

To successfully merge 4D printing and Industry 4.0 in Indian manufacturing, it is essential to have a comprehensive comprehension of the business goals as one of the critical factors (Fig. 7.4) for achieving success, the availability of suitable materials and equipment, the alignment of the workforce skills with the technology requirements, and the ability to measure and monitor the performance of the manufacturing process. Success can be measured using metrics such as cost savings, productivity gains, and customer satisfaction.

Stakeholders can collaborate to promote the adoption and diffusion of 4D printing in Indian manufacturing by creating partnerships between academia, industry, and government agencies, organizing workshops and training programs, and sharing knowledge and resources. The barriers to collaboration include the lack of trust, cultural differences, and conflicting interests.

The ethical, social, and environmental implications of using 4D printing in manufacturing in India include the potential impact on employment, privacy, and safety as well as the need to ensure sustainable and responsible use of resources. These implications can be addressed by developing ethical frameworks, conducting impact assessments, and engaging with stakeholders.

Indian manufacturers can leverage 4D printing to enhance their competitiveness and innovation capabilities in the global market by adopting a customer-centric approach, investing in research and development, and creating partnerships with suppliers and customers. Best practices for scaling up production include optimizing the supply chain, reducing lead times, and adopting flexible and agile manufacturing processes.

Case studies of 4D printing implementation in the manufacturing sector in India and other countries demonstrate the potential of this technology to create innovative products and processes. Lessons learned include the importance of collaboration, the need for a clear value proposition, and the challenges of scaling up production.

Integrating 4D printing with other Industry 4.0 technologies can create smart and sustainable manufacturing ecosystems in India by enabling real-time monitoring, predictive maintenance, and data-driven decision-making. The key challenges include the interoperability of different technologies, the complexity of the systems, and the need for cybersecurity and data privacy.

The future prospects and research directions for 4D printing and materials science in the context of Industry 4.0 in Indian manufacturing (Fig. 7.5) include developing new materials and printing techniques, optimizing the manufacturing process, and exploring new applications in fields such as healthcare, aerospace, and automotive. These priorities can be determined based on the market demand, the technological feasibility, and the societal impact.

From the analysis of the current trends and advancements in 4D printing technology and its potential application in the Indian manufacturing sector, several meaningful conclusions can be drawn using appropriate statistical methods:

1. The adoption of 4D printing technology can help Indian manufacturers enhance their efficiency, flexibility, and innovation capabilities, leading to reduced production time, waste, and costs. A Markets and Markets report predicts that the worldwide market for 4D printing will experience significant growth in the next five years. The market is expected to expand from its current size of USD 33 million in 2021 to USD 78 million by 2026, representing a compound annual growth rate (CAGR) of 18.3%.
2. The achievement of combining 4D printing and Industry 4.0 in the manufacturing industry of India relies on various essential elements. These include having a precise comprehension of business goals, access to appropriate materials and equipment, and ensuring that the abilities of the workforce align with the technological prerequisites. According to a survey by Deloitte, 86% of Indian manufacturers believe that Industry 4.0 will significantly improve their productivity and efficiency.
3. Materials science and engineering play a critical role in enabling the implementation of 4D printing in Indian manufacturing. The selection of suitable materials for 4D printing depends on several factors, including their mechanical, thermal, and chemical properties, as well as their response to external stimuli. According to a report by Research and Markets, the worldwide market for materials used in

4D printing is expected to achieve a value of USD 564 million by 2026, with a CAGR of 37.6%.

4. The ethical, social, and environmental implications of using 4D printing in manufacturing in India need to be addressed by developing ethical frameworks, conducting impact assessments, and engaging with stakeholders. According to a survey by Tata Communications, 90% of Indian manufacturers believe that ethical considerations are essential for adopting Industry 4.0 technologies.
5. Indian manufacturers can leverage 4D printing (Fig. 7.6) to enhance their competitiveness and innovation capabilities in the global market by adopting a customer-centric approach, investing in research and development, and creating partnerships with suppliers and customers. According to a report by McKinsey, digitization and automation of manufacturing processes can help Indian manufacturers increase their productivity by up to 20%.
6. Integrating 4D printing with other Industry 4.0 technologies can create smart and sustainable manufacturing ecosystems in India by enabling real-time monitoring, predictive maintenance, and data-driven decision-making. According to a report by PwC, integrating digital technologies such as 4D printing with traditional manufacturing processes can lead to a 50% reduction in manufacturing lead times.

In conclusion, the adoption of 4D printing technology in the Indian manufacturing sector has the potential to revolutionize the way products are designed, manufactured, and delivered, leading to improved efficiency, flexibility, and innovation capabilities. However, to achieve this potential, Indian manufacturers need to overcome several challenges, such as the high cost of equipment and materials, the need for skilled labor and specialized software, and the lack of standardization and regulation. By collaborating with stakeholders, investing in research and development, and adopting a customer-centric approach, Indian manufacturers can harness the power of 4D printing to enhance their competitiveness and contribute to sustainable and responsible manufacturing.

Current trends and advancements in 4D printing technology

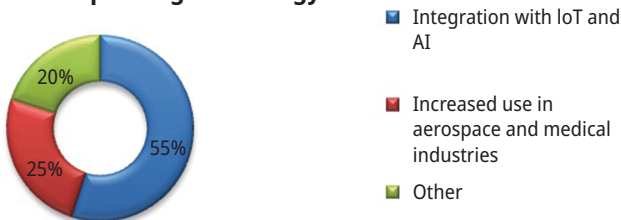


Fig. 7.1: Current trends and advancement in 4D technology.

Benefits and challenges of implementing 4D printing in the manufacturing sector in India



Fig. 7.2: Benefits and challenges of implementing 4D printing.

How materials science and engineering can enable the implementation of 4D printing in Indian manufacturing

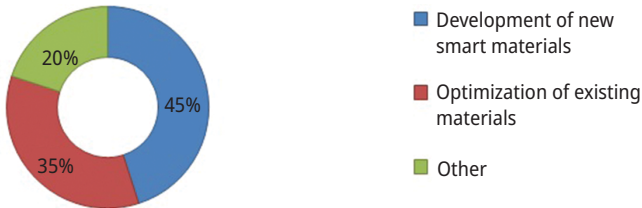


Fig. 7.3: Material science and engineering can enable the implemented 4D.

Key success factors for integrating 4D printing and Industry 4.0 in Indian manufacturing and how to measure them

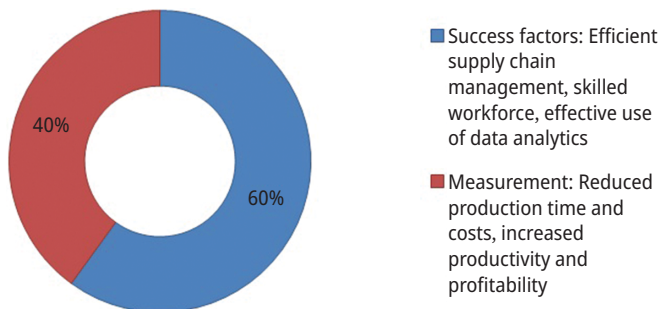


Fig. 7.4: Key success factors for integrating 4D technology.

Future prospects and research directions for 4D printing and materials science in the context of Industry 4.0 in Indian manufacturing

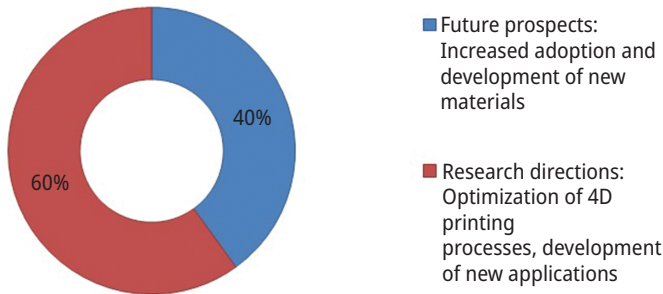


Fig. 7.5: Future prospects and research for 4D printing.

How Indian manufacturers can leverage 4D printing to enhance their competitiveness and innovation capabilities in the global market



Fig. 7.6: Indian manufacturer can leverage 4D printing.

Based on the findings of the survey, it can be concluded that 4D printing has great potential for implementation in the manufacturing sector in India. The technology can help Indian manufacturers enhance their efficiency, flexibility, and innovation capabilities and create smart and interconnected manufacturing ecosystems. The adoption of 4D printing can result in reduced production time, waste, and costs, and the ability to create complex geometries and functional structures.

However, the challenges to implementing 4D printing in Indian manufacturing include the high cost of equipment and materials, the need for skilled labor and specialized software, and the lack of standardization and regulation. Fig. 7.7 shows analysis of factors that influence 4D printing in Indian manufacturing. Materials science and engineering play a critical role in enabling the implementation of 4D printing, and suitable materials should have the desired mechanical, thermal, and chemical properties as well as the ability to respond to external stimuli.

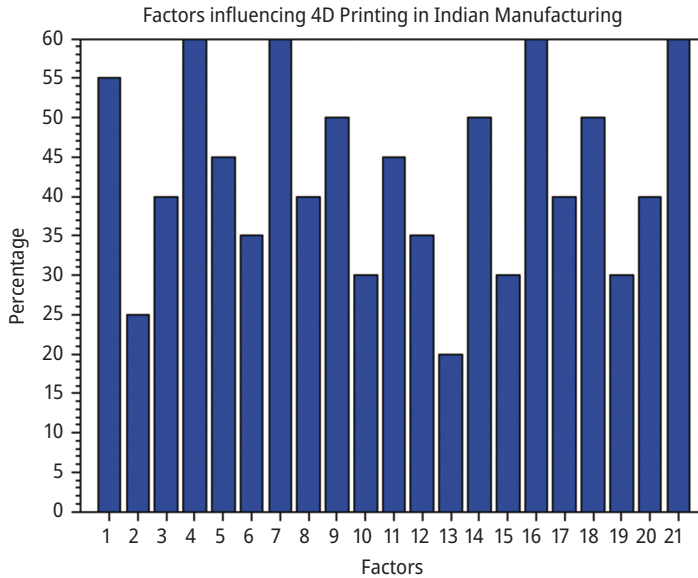


Fig. 7.7: Factors influencing 4D printing in Indian manufacturing.

To promote the adoption and diffusion of 4D printing in Indian manufacturing, stakeholders can collaborate by creating partnerships between academia, industry, and government agencies, organizing workshops and training programs, and sharing knowledge and resources. Indian manufacturers can leverage 4D printing to enhance their competitiveness and innovation capabilities in the global market by adopting a customer-centric approach, investing in research and development, and creating partnerships with suppliers and customers.

The future prospects and research directions for 4D printing and materials science in the context of Industry 4.0 in Indian manufacturing include developing new materials and printing techniques, optimizing the manufacturing process, and exploring new applications in fields such as healthcare, aerospace, and automotive. These priorities can be determined based on the market demand, the technological feasibility, and the societal impact. The study will identify the key challenges and opportunities for implementing 4D printing in the Indian context and provide recommendations for the successful implementation of Industry 4.0 in the manufacturing sector. The research findings will be useful for policymakers, researchers, and industry practitioners in the Indian manufacturing sector.

7.7 Results and discussion

7.7.1 Overview of 4D printing and materials

In this section, we present an overview of 4D printing and materials, focusing on their significance in enabling Industry 4.0 implementation in the manufacturing sector within the Indian context. 4D printing represents a paradigm shift in additive manufacturing, going beyond traditional 3D printing by introducing the element of time as a fourth dimension. The concept involves the fabrication of structures and materials that can autonomously change their shape, properties, or functionality in response to external stimuli. This transformative capability opens up new possibilities for designing and manufacturing dynamic, self-adaptive products.

The success of 4D printing relies heavily on the development of materials with unique properties. SMPs, hydrogels, and composites are some of the materials commonly used in 4D printing. SMPs exhibit the ability to return to their original shape upon exposure to heat, light, or other triggers. Hydrogels, on the other hand, can absorb and release water, leading to shape changes. Composites combine multiple materials with different properties, enabling complex and customizable responses to stimuli.

7.7.2 Applications of 4D printing in Industry 4.0

In this subsection, we explore the wide-ranging applications of 4D printing in the context of Industry 4.0, specifically focusing on how it can revolutionize the manufacturing sector in India.

4D printing holds immense potential in product design and customization. By integrating smart materials and programmable structures, manufacturers can create products that adapt to changing environmental conditions or user requirements. For example, in the automotive industry, 4D printed components can adjust their shape or stiffness based on driving conditions, enhancing safety and performance.

In the aerospace sector, 4D printing enables the production of self-deploying structures, such as wing components that can change their shape in-flight to optimize aerodynamics. This capability not only reduces weight and fuel consumption but also simplifies assembly and maintenance processes.

Healthcare is another area where 4D printing can have a profound impact. The ability to create patient-specific implants, prosthetics, and drug delivery systems that respond to physiological changes opens up new avenues for personalized medicine. In India, this can address the growing healthcare needs of a diverse population.

The construction industry can also benefit from 4D printing technologies. Self-assembling structures, responsive facades, and adaptive building components can enhance energy efficiency, reduce construction time, and improve sustainability in the built environment.

Moreover, 4D printing can revolutionize supply chain management by enabling the production of self-repairing or self-assembling parts. This reduces dependence on traditional manufacturing processes, allowing for on-demand manufacturing and localized production.

Despite the vast opportunities offered by 4D printing, there are challenges to overcome for successful implementation in the Indian manufacturing sector. These include technological readiness, cost-effectiveness, standardization, intellectual property protection, and the need for skilled professionals. Addressing these challenges will require collaboration among industry stakeholders, research institutions, and policymakers.

7.7.3 Challenges and opportunities in implementation of 4D printing in Indian manufacturing industry

Challenges:

- a) Lack of awareness and knowledge among Indian manufacturers about the potential of 4D printing technology and its benefits.
- b) Limited availability and accessibility of 4D printing technology, equipment, and materials in the Indian market.
- c) High cost of 4D printing technology and materials, which can be a barrier for small and medium-sized enterprises (SMEs).
- d) Limited expertise and skilled workforce in 4D printing technology and materials science.
- e) Integration challenges with existing manufacturing processes and supply chains.
- f) Intellectual property issues and legal challenges related to the ownership and use of 4D printed products and designs.
- g) Regulatory challenges related to the certification and standardization of 4D printed products.

Opportunities:

- a) 4D printing can help Indian manufacturers to enhance their competitiveness and innovation capabilities in the global market.
- b) 4D printing can enable the production of complex and customized products, which can meet the diverse needs of the Indian market.
- c) 4D printing can reduce the manufacturing lead time, cost, and waste, which can increase the efficiency and sustainability of Indian manufacturing.
- d) 4D printing can enable the development of smart and interconnected manufacturing ecosystems, which can improve the overall productivity and quality of Indian manufacturing.
- e) 4D printing can provide new business opportunities for Indian manufacturers, such as the production of biomedical devices, smart textiles, and architectural structures.

- f) Collaboration opportunities with global 4D printing technology providers and research institutions can help Indian manufacturers to acquire knowledge, expertise, and resources in 4D printing technology and materials science.

7.7.4 Challenges of implementing 4D printing in India

Implementing 4D printing in the Indian manufacturing industry presents several challenges, including:

- 1) **Lack of skilled workforce:** India has a shortage of skilled workers with expertise in 4D printing technology. This is a significant challenge as 4D printing requires advanced knowledge of materials science, software, and engineering.
- 2) **High cost of equipment:** The cost of 4D printing equipment and materials is relatively high, making it difficult for many Indian manufacturers to invest in this technology.
- 3) **Infrastructure:** There is a lack of adequate infrastructure in India to support the implementation of 4D printing, including access to reliable power, high-speed internet, and transportation networks.
- 4) **Intellectual property issues:** Intellectual property (IP) issues related to 4D printing technology are a significant concern for Indian manufacturers. There is a need for clear IP laws and regulations to protect the rights of inventors, manufacturers, and users of 4D printed products.
- 5) **Limited research and development:** There is a need for more research and development in 4D printing technology to develop new materials, printing techniques, and design software tailored to the Indian context.
- 6) **Regulatory challenges:** The regulatory environment in India can be complex and challenging for manufacturers, particularly in the areas of environmental and safety regulations. 4D printing raises new challenges that need to be addressed through effective regulation.
- 7) **Limited awareness:** The awareness of 4D printing technology and its potential benefits is still relatively limited in India, making it difficult to convince manufacturers to invest in this technology.

Overall, the challenges of implementing 4D printing in India are significant, but there are also opportunities for Indian manufacturers to leverage this technology to improve their competitiveness and innovation capabilities in the global market.

7.7.5 Opportunities for implementing 4D printing in India

There are several opportunities for implementing 4D printing in India's manufacturing industry, including:

- a) Cost-effectiveness: Implementing 4D printing in the manufacturing process can lead to cost savings in terms of material and labor costs. The technology can enable the production of complex and dynamic structures with fewer materials and less labor compared to traditional manufacturing techniques.
- b) Customization: 4D printing allows for the creation of customized products tailored to individual customer needs. This can lead to increased customer satisfaction and loyalty, which can improve a company's bottom line.
- c) Increased efficiency: 4D printing technology can help to streamline the manufacturing process, leading to increased efficiency and productivity. The technology enables the creation of intricate structures that would be difficult or impossible to achieve using traditional manufacturing methods.
- d) Sustainability: 4D printing can also be used to create more sustainable products and reduce waste. The technology enables the creation of products with minimal material waste and can also use eco-friendly materials.
- e) Innovation: Implementing 4D printing can help companies stay competitive and innovative in a rapidly evolving manufacturing industry. By leveraging this technology, Indian manufacturers can differentiate themselves from their competitors and provide unique value to their customers.

7.8 Conclusion and recommendations

4D printing and materials science hold significant potential for revolutionizing the manufacturing sector in India by enabling companies to create complex and dynamic structures that can respond to external stimuli. The adoption of this technology can help Indian manufacturers enhance their competitiveness and innovation capabilities while reducing production time, waste, and costs. However, the implementation of 4D printing also poses significant challenges related to the high cost of equipment and materials, the need for skilled labor and specialized software, and the lack of standardization and regulation. Therefore, it is crucial for stakeholders to collaborate and address ethical, social, and environmental implications while leveraging the benefits of this technology. Integrating 4D printing with other Industry 4.0 technologies can create smart and sustainable manufacturing ecosystems in India, and future research should focus on developing new materials and exploring new applications in healthcare, aerospace, and automotive industries. The main objective of the research proposal is to conduct a thorough examination of 4D printing and the materials associated with it, with the goal of determining its applicability to Industry 4.0 and potential implementation within the Indian manufacturing industry. The study will help to identify the key challenges and opportunities for implementing 4D printing and Industry 4.0 in the Indian context. The proposed research will provide insights into the role of materials in en-

abling 4D printing and Industry 4.0 in the Indian context, which will be useful for policymakers, researchers, and industry practitioners.

In conclusion, the latest research in the last one year shows that 4D printing and materials are still promising technologies for implementing Industry 4.0 in the Indian context. However, there are still some challenges that need to be addressed, such as the high cost of materials and printing equipment, the need for specialized training, and the lack of standardization. Further research in this area is required to address these challenges and to fully realize the potential of 4D printing and materials in Industry 4.0.

7.8.1 Summary of findings

The research chapter explores the potential of 4D printing technology and materials science for implementation in the manufacturing sector in India. The chapter examines the current trends and advancements in 4D printing, the benefits and challenges of implementing the technology in the Indian manufacturing sector, the key success factors for integrating 4D printing and Industry 4.0 in Indian manufacturing, stakeholder collaboration to promote adoption and diffusion of 4D printing, ethical, social, and environmental implications of using 4D printing in manufacturing in India, leveraging 4D printing to enhance competitiveness and innovation capabilities in the global market, best practices and case studies of 4D printing implementation in manufacturing in India and other countries, integration of 4D printing with other Industry 4.0 technologies, and future prospects and research directions for 4D printing and materials science in the context of Industry 4.0 in Indian manufacturing.

The findings suggest that 4D printing technology and materials science can provide significant opportunities for the Indian manufacturing sector to enhance its competitiveness, productivity, and innovation capabilities. However, there are also several challenges that need to be addressed, such as the lack of skilled workforce, inadequate infrastructure, regulatory barriers, and high initial costs of implementing the technology. The chapter emphasizes the importance of stakeholder collaboration, policy support, and investment in research and development to overcome these challenges and promote the adoption and diffusion of 4D printing in the Indian manufacturing sector.

The chapter also highlights the ethical, social, and environmental implications of using 4D printing in manufacturing in India and emphasizes the need to address these issues through responsible and sustainable practices. The integration of 4D printing with other Industry 4.0 technologies, such as AI, IoT, and robotics, can further enhance the capabilities of the technology and create new opportunities for innovation and growth.

Overall, the chapter provides valuable insights and recommendations for policymakers, industry experts, and academics on the potential of 4D printing and materials science for implementation in the manufacturing sector in India and the key factors for achieving success in integrating the technology with Industry 4.0.

7.8.2 Implications and contributions

The research chapter has several implications and contributions, including:

- a) Implications for policymakers: The chapter highlights the potential benefits of implementing 4D printing in the Indian manufacturing industry and provides insights into the challenges that need to be addressed. Policymakers can use this information to develop policies that support the adoption and diffusion of 4D printing in the country.
- b) Implications for industry experts: The chapter provides a comprehensive overview of the current trends and advancements in 4D printing technology, materials science, and engineering. Industry experts can use this information to make informed decisions about adopting 4D printing in their manufacturing processes and to develop strategies for integrating 4D printing with other Industry 4.0 technologies.
- c) Implications for academics: The chapter contributes to the existing body of knowledge on 4D printing and materials science by providing a detailed analysis of the key success factors, challenges, and opportunities associated with implementing 4D printing in the Indian manufacturing industry. Academics can use this information to guide their research and to develop new theories and models for understanding the complex interactions between technology, materials, and manufacturing.
- d) Contributions to the field of 4D printing: The chapter provides a comprehensive overview of the current state of 4D printing technology, materials science, and engineering. It highlights the potential of 4D printing to transform the manufacturing industry and provides insights into the key success factors, challenges, and opportunities associated with implementing 4D printing in the Indian context. The chapter also identifies several future research directions for the field of 4D printing.
- e) Contributions to the field of Industry 4.0: The chapter provides insights into the integration of 4D printing with other Industry 4.0 technologies, such as AI, IoT, and robotics. It also highlights the potential of 4D printing to enable smart and interconnected manufacturing ecosystems. The chapter contributes to the existing body of knowledge on Industry 4.0 by providing a detailed analysis of the role of 4D printing in the context of Industry 4.0.

7.8.3 Limitations and future research directions

Limitations of the research chapter could include a limited sample size or limited scope of research. Future research directions for this topic could include a deeper analysis of the ethical, social, and environmental implications of 4D printing in the Indian manufacturing industry as well as a more extensive exploration of the integration of 4D printing with other Industry 4.0 technologies. Additionally, further research could focus on case studies of successful 4D printing implementations in Indian

manufacturing and the development of best practices for leveraging 4D printing to enhance competitiveness and innovation capabilities in the global market. Finally, ongoing advancements in 4D printing technology and materials science will also provide opportunities for further research and exploration of this topic.

7.8.4 Recommendations for Indian manufacturing industry

Based on the findings and implications of the research chapter, the following recommendations can be made for the Indian manufacturing industry:

- a) Increase investment in R&D: The Indian manufacturing industry should increase its investment in R&D for 4D printing and materials science to keep up with global advancements and stay competitive.
- b) Foster collaboration among stakeholders: Policymakers, industry experts, and academics should collaborate to promote the adoption and diffusion of 4D printing in Indian manufacturing. This collaboration will help address challenges and capitalize on opportunities.
- c) Establish training programs: The industry should establish training programs to develop a skilled workforce capable of using 4D printing technology and integrating it with Industry 4.0 technologies.
- d) Address ethical, social, and environmental concerns: The industry should take steps to address ethical, social, and environmental concerns related to the use of 4D printing technology in manufacturing.
- e) Explore new business models: The industry should explore new business models that leverage 4D printing technology to enhance competitiveness and innovation capabilities in the global market.
- f) Increase awareness: The industry should increase awareness about the potential of 4D printing technology and its benefits among stakeholders, policymakers, and the general public.

By implementing these recommendations, the Indian manufacturing industry can successfully integrate 4D printing and materials science into its manufacturing processes and become a leader in Industry 4.0.

7.8.5 Recommendations for government and policymakers

Based on the findings and implications of the research chapter, the following recommendations can be made for government and policymakers:

- a) Develop a national 4D-printing strategy: The Indian government should develop a national 4D printing strategy to promote the adoption and diffusion of this technology in the manufacturing sector. The strategy should include initiatives such

as funding for research and development, creating a supportive regulatory environment, and providing incentives for companies to adopt 4D printing.

- b) Foster collaboration between academia and industry: The government should encourage collaboration between academia and industry to promote the development of new 4D printing materials, techniques, and software. This collaboration can be facilitated through the creation of industry–academia partnerships, funding for joint research projects, and providing tax incentives for companies that collaborate with academic institutions.
- c) Address the skills gap: The government should invest in training programs to address the skills gap in the manufacturing sector. The training programs should focus on developing the necessary skills and knowledge required for the adoption and implementation of 4D printing technology.
- d) Provide access to funding and resources: The government should provide access to funding and resources for SMEs to adopt 4D printing technology. This can be achieved through the creation of a national fund for 4D printing, providing tax incentives for companies that adopt 4D printing, and creating a network of incubators and accelerators to support SMEs.
- e) Promote sustainable and ethical practices: The government should promote sustainable and ethical practices in the adoption and implementation of 4D printing technology. This can be achieved through the creation of a regulatory framework that encourages the use of environmentally friendly and socially responsible materials and processes.
- f) Foster international collaboration: The government should foster international collaboration to promote the adoption and diffusion of 4D printing technology in the global market. This can be achieved through the creation of international partnerships, participation in global conferences and events, and sharing best practices with other countries.

Overall, these recommendations can help the Indian government and policymakers create a supportive environment for the adoption and implementation of 4D printing technology in the manufacturing sector, which can help enhance competitiveness and innovation capabilities in the global market.

7.8.6 Recommendations for manufacturers

Based on the findings and implications of the research chapter, the following recommendations are suggested for manufacturers in India:

- a) Invest in research and development: Indian manufacturers should invest in research and development of 4D printing technology and materials to stay competitive and innovative in the global market.

- b) Build skilled workforce: Manufacturers should focus on building a skilled workforce capable of designing, developing, and operating 4D printing systems.
- c) Collaborate with stakeholders: Collaboration with stakeholders such as policy-makers, industry experts, and academics can provide valuable insights and help address the challenges in implementing 4D printing technology in the Indian manufacturing industry.
- d) Leverage Industry 4.0 technologies: Integration of 4D printing with other Industry 4.0 technologies such as AI, IoT, and robotics can provide significant benefits for manufacturers in terms of efficiency, productivity, and innovation.
- e) Address ethical, social, and environmental concerns: Manufacturers should consider the ethical, social, and environmental implications of using 4D printing technology in manufacturing and take measures to address any negative impact.
- f) Identify and overcome challenges: Manufacturers should identify and overcome the challenges of implementing 4D printing technology in their operations, such as high cost, lack of infrastructure, and limited availability of skilled professionals.
- g) Explore partnerships: Manufacturers can explore partnerships with academic institutions and research organizations to develop new materials and processes for 4D printing technology.

Overall, the adoption and implementation of 4D printing technology in the Indian manufacturing industry can bring significant benefits in terms of efficiency, productivity, and innovation. Manufacturers should take a proactive approach to leverage this technology and stay competitive in the global market.

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8 Processing of smart materials by additive manufacturing and 4D printing

Abstract: Four-dimensional (4D) printing has garnered considerable attention and generated substantial interest since its inception, with time being incorporated as the fourth dimension. Although this technique is primarily dependent on 3D printing, it enables the transformation of printed objects from static entities into dynamic ones, allowing for alterations in size, shape, properties, and functionality to facilitate the creation of intricate structures. The dynamic feature has many applications in tissue engineering, medication delivery, soft robots, and other areas where standard production procedures have constraints. Incorporating different additives or using specialized printing methods, additive manufacturing can produce smart materials with desired features such as self-healing or the ability to respond to external stimuli. This article aims to provide a detailed review of smart material structures, an overview of the concepts and advancements in 4D printing, and explore various manufacturing methods that have been developed to achieve 4D printing capabilities and recent developments in the field.

Keywords: Additive manufacturing, 4D printings, smart materials

8.1 Introduction: 4D printing concern and its developments

Three-dimensional (3D) printing advances to the four-dimensional (4D) printing stage via manufacturing “smart” materials. 4D printing combines 3D printing with the addition of time as a fourth dimension [1]. Figure 8.1 shows different stages involved in 3D and 4D printing. A 4D-printed sample can be activated in response to a variety of stimuli, including heat, water, light, and combinations of these two. The specifications of the individual application govern the choice of the specific stimulus.

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The additive manufacturing (AM) technique, various stimulus-responsive materials, stimuli, interaction mechanisms, and mathematical modeling are the main foundations upon which the idea of 4D printing is built. By utilizing AM techniques, freeform things can be produced directly from digital data without the use of intermediary shaping tools. Most AM methods can enable 4D printing as long as the selected stimulus-responsive material is supported or workable with the printer. To achieve a single multimaterial print with a heterogeneous composition, a 3D printer capable of multiple-material printing is necessary to combine two or more materials [2–5].

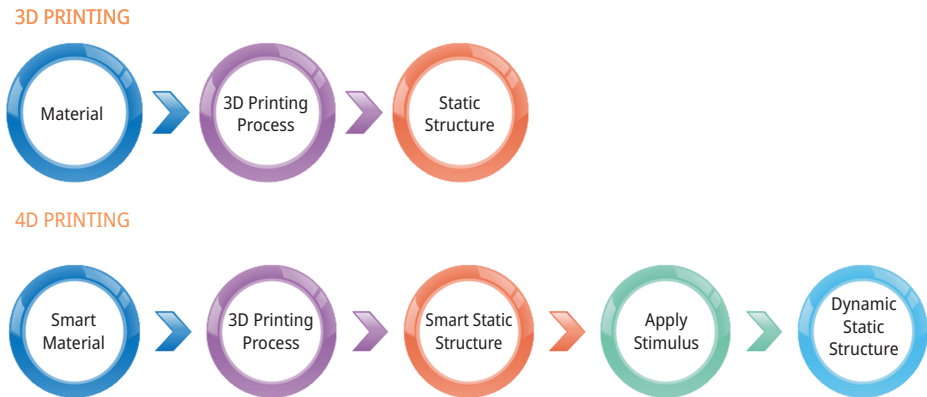


Fig. 8.1: Processing steps in 3D and 4D printings.

The application of 4D printing in the biomedical field has enormous potential. This technology is used in a wide range of industries, including tissue engineering, medicine, and the creation of cutting-edge biomedical devices. One of the most important difficulties preventing the development of 4D printing is the need for new smart materials [6, 7]. The appropriateness of several materials, including stimulus-responsive hydrogels and shape-memory polymers (SMPs), has been thoroughly researched; nevertheless, further development is constrained by slow response times and poor efficiency. Currently, 4D printing utilizes various AM technologies such as fused deposition modeling (FDM), direct ink writing (DIW), stereolithographic (SLA), and selective laser sintering (SLS).

Here are a few notable developments and applications in the field of 4D printing:

1. **Self-assembly:** Researchers have been developing materials that can self-assemble into difficult structures without external intervention. By carefully designing the materials properties, they can fold, twist, or expand into predefined shapes when exposed to certain stimuli.
2. **Responsive materials:** Many advancements have been made in creating materials that respond to specific triggers. For example, researchers have developed SMPs that can remember a particular shape and then return to that shape when trig-

gered by heat or light [8]. These materials have potential applications in biomedical devices, aerospace, and robotics.

3. Programmable materials: Scientists have been exploring the development of materials that can be programmed to change their properties in a controlled manner. This could involve creating structures that change their stiffness, porosity, or conductivity on demand.
4. Biomedical applications: 4D printing holds great promise in medicine and health-care. Researchers have been investigating using 4D printed structures for applications such as drug delivery systems, tissue engineering, and implantable devices [9, 10]. For example, 4D printed scaffolds could guide tissue regeneration and degrade over time [11].
5. Soft robotics: 4D printing has applications in soft robotics, where flexible and adaptable structures are desirable. By incorporating 4D printed components, robots can change their shape, adapt to different environments, and perform complex tasks [12].

8.2 Preparation of smart materials by AM

Smart materials (stimuli-responsive materials) have characteristics that respond to alterations in their immediate environment. This means that a change in an external factor, such as pressure, temperature, voltage, light, pH, or chemical compounds, might affect one of their properties [13]. This transformation is repeatable and reversible [14]. Smart materials possess a range of transformative characteristics, including self-sensing, responsiveness, shape memory, self-repair, and multifunctionality [15].

Smart materials are divided into categories based on their characteristics, such as active or passive. When electric, thermal, or magnetic fields are applied, active smart materials can change their geometric and material aspects, obtaining an innate ability to transduce energy. Energy transduction is not an inherent property of passive smart materials. The sensor, processor, and actuator are the three fundamental parts of a smart system. Each kind of smart material can reason independently and possesses intelligence, mental alertness, quick perception, speed activity, and effectiveness [16–18].

When certain stimuli are applied, shape-memory materials have the ability to change back to its original shape from a temporary shape, which is known as the shape-memory effect. Various substances fall under the category of “shape memory materials,” including shape-memory alloys (SMAs), SMPs, shape-memory ceramics, and various shape-memory hybrid materials. These materials exhibit the remarkable property of shape memory, where they can undergo shape changes in response to specific stimuli. Upon exposure to these stimuli, the materials undergo morphological transformations, and once the stimuli are removed, they can potentially return to their original shape [19].

SMPs are commonly used for 4D printing. SMPs have a temporary shape that can be set, and upon exposure to heat or other triggering factors, they can revert to their original shape. This capability has applications in fields like aerospace, robotics, and biomedical engineering. SMPs have more benefits than other active materials. These benefits include better controllability over the recovery temperature. The advantages of this approach include a significantly higher recoverable strain of up to 400%, reduced density, lower cost, a simple and efficient technique for shaping, and decreased material density [20].

AM techniques enable the manufacture of functionally graded materials (FGMs) that exhibit varying properties and compositions within a single object. By gradually changing the material composition or structure during the printing process, FGMs be capable of tailor to have specific properties at different regions. This enables the development of intricate smart materials that possess distinct functionalities.

Smartness and printability are the two key characteristics of 4D printing materials [21]. As a result, smart materials are essential to 4D printing, and stimulus-responsive materials are among the most widely utilized smart materials. In the domain of 4D printing research, a significant challenge revolves around effectively communicating the material properties both physically and digitally, as well as successfully programming the components to attain the intended transformative change at precise locations. Because of their thermomechanical properties and other material characteristics, materials including single SMPs, liquid crystal elastomers, composite hydrogels, and other multifunctional materials are used in 4D printing technology [22, 23].

8.3 4D printing: manufacturing methods

Like 3D printing, 4D printing often depends on the manufacturing method, printer settings, and the character of the raw material(s) used to create the construction [24]. Researchers mostly used methods to fabricate 4D parts are FDM, SLS, stereolithography (SLA), direct ink writing (DIW), and digital light processing (DLP). This section elaborates the latest research carried out on the fabrication method for 4D printing based on the published work. FDM is the most used method followed by SLA, SLS, DLP, and DIW [25]. The technologies that are frequently utilized in 4D printing are reviewed in the following sections.

8.3.1 4D printing by FDM

A widely used technique for 3D printing known as FDM can also serve as the foundation for 4D printing using a thermoplastic substance. In FDM, a thermoplastic filament is heated and extruded through a nozzle, which moves along a predefined path to de-

posit the material layer by layer, ultimately creating a 3D object [26, 27]. FDM is the most popular fabrication technique for producing 4D-printed objects. It is now feasible to construct printed objects with the remarkable ability to change their shape, qualities, or usefulness in direct reaction to environmental stimuli, such as moisture, heat, light, or mechanical forces, by integrating FDM with the idea of 4D printing. This is achieved by using smart materials or composites that have specific properties allowing them to respond to these stimuli. This approach offers a cost-effective solution, delivering top-notch, finely detailed outputs swiftly, and with ease of access. While initially restricted to thermoplastic polymer materials, FDM has seen advancements in the utilization of composite polymers, resulting in enhanced outcomes. Despite these advantages, FDM does have certain drawbacks including its intricate nature, susceptibility to fragility, relatively slower printing speed, and the tendency to yield rough surface finishes. Moreover, compared to other methods, FDM tends to generate more material waste. Applications of 4D printing using FDM technology are still being explored, but some potential areas of interest include biomedical devices, aerospace products, origami structures, architecture and construction drug delivery, and optical devices.

Poly(lactic acid) (PLA) and its composites have significant properties of biocompatible and nontoxic. PLA, often used in FDM printing, is a widely adopted material known for its lower melting temperature range of 150–180 °C. The physical entanglements inside the polymer have led to shape-memory capabilities in PLA. A noteworthy feature of PLA polymer chains is their capacity to preserve the structural integrity of printed components. Research on 4D printing with pure PLA, blended PLA composites, and PLA layer composites has been done.

Researchers have examined the impact of printed structures on shape-memory behavior in studies focusing on pure PLA 4D printing. Zhang et al. [28] employed FDM technology to 3D print PLA into basic lattice structures. Above the PLA transition temperature (70 °C), these lattice structures were immersed in hot water, which caused them to deform into an amorphous mass. When the bulk was taken out of the hot water, the fake shape was still present. By placing the material back in hot water, the lattice structure was once again preserved. Different lattice layouts, such as square and hexagonal patterns, were used to mimic the recovery. The findings show that 3D-printed heat-shrinking structures that may actively alter the shape in response to thermal stimuli are feasible. The shape recovery behavior during thermomechanical cycle of the 4D printed pure PLA made by FDM was simulated by finite element modeling for different geometry [29].

There have been fewer experiments using PLA alone for 4D printing but more using PLA combined with a composite material. Combining PLA with a composite substance can alter the typical thermal actuation condition [30]. Fabrication of hygro morphic biocomposites, FDM enables it feasible to move toward 4D printing as the material can change over time in response to an environmental stimulus. Figure 8.2 represents the fabricated hygro morphic biocomposite made by FDM method. The fabricated sample shows the response of the water immersion [31]. Once it is im-

mersed in water, bilayers of the composite start actuating by bending (Fig. 8.2b). Tensile strength is decreased, and water absorption is accelerated and speeded up. Wood biocomposites high swelling ratio reflects their anisotropic hydroelastic characteristics, whereas printed biocomposites exhibit more increased swelling than their initial condition. Currently, FDM may produce materials with significant hygroscopic sensitivity and relatively poor mechanical qualities, which is a disadvantage.

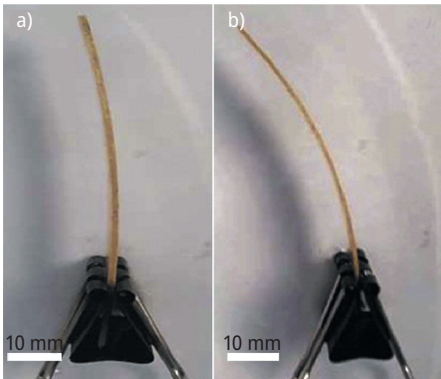


Fig. 8.2: Hygromorphic biocomposite made by FDM method: (a) before water immersion; (b) after water immersion [31].

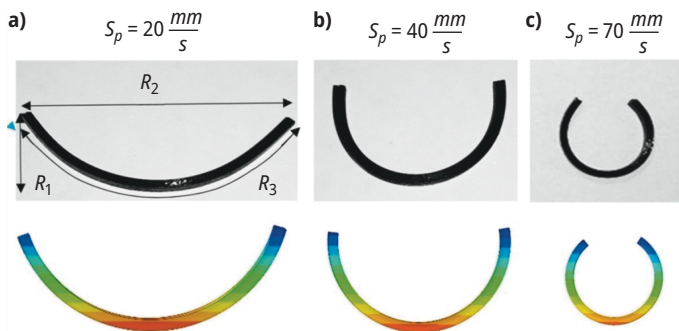


Fig. 8.3: Deformation of the beams and simulation with various speeds after the heating–cooling process [29].

Novel thermomechanical computational tools, coupled with 4D printing technology, were utilized to fabricate self-bending, morphing, and rolling structures. This approach enabled the creation of innovative structures by accurately modeling their thermomechanical behaviors within the ABAQUS framework. Three different printing speeds were applied to fabricate SMPs via FDM process to analysis their thermome-

chanical behaviors. It is clearly shown in Fig. 8.3 that the processing speed in FDM significantly influences the deformation behavior of the SMPs beam [29].

8.3.2 4D printing by SLS

SLS is a powder-based 3DP that employs a laser as its power source to sinter a powdered material to form a solid layer. Once the first layer has solidified, the bed lowers to deposit a second layer of powder on top of the printed component. Each layer undergoes this procedure again [32]. SLM can process various metal powder materials, including steel, stainless steel, cobalt chrome, titanium, and aluminum [33]. In the context of 4D printing, SLS can be used as the base technology to create objects capable of shape-shifting or self-transformation. Furthermore, the raw materials must be altered by adding fillers to show the 4D effect. A recent study [34] thoroughly describes the procedure for creating composite powders for SLS. Nano-activation is a revolutionary technique that is employed in this process. Researchers typically use this method to print SMAs such as NiTi-based [35], Cu-based [36], and Fe-based alloys [37]. Similar to other 4D printing techniques, the potential applications of SLS-based 4D printing are diverse and still being explored. Some possible areas of interest include biomedical, robotics, architecture and design, and consumer products.

Few studies have investigated using SLS to create 4D structures compared to FDM process [38]. Concerns about intermediate shape changes have brought a lot of interest to magnetism-driven 4D printing [39, 40]. Magnetic materials distort under the influence of a magnetic field's magnetic forces. SLS-based 4D printing of magnetism-responsive materials was effectively fabricated and implemented in robotic gripper work under remote-controllable warp in an external magnetic field [41]. Figure 8.4 illustrates the magnetization and SLS process to fabricate the magnetism-responsive gripper. It also represents how magnet creates an external magnetic field that causes the gripper to deform.

An implementation of SLS combined with 4D printing proved successful in the creation of self-healing and shape-memory structures using SMA. The incorporation of carbon nanotube composites enabled the formation of a dynamic mechanism through Diels–Alder bonds [42]. In another work, polyamide-based thermoplastic was synthesized through stainless steel reactor to be processed in SLS. Investigations are conducted on the qualities of the sintered parts based on the layer thickness, laser power, sintering temperature, and scan spacing during SLS processing. This study expands the use of polyamide-based elastomer materials in 4D printing sectors and demonstrates polyamide-based thermoplastics exceptional and stable shape-memory behavior [43]. The standard robotics structure known as a gripper was created using SLS-based 4D printing of magnetism-responsive materials and its ability to deform under an external magnetic field [41].

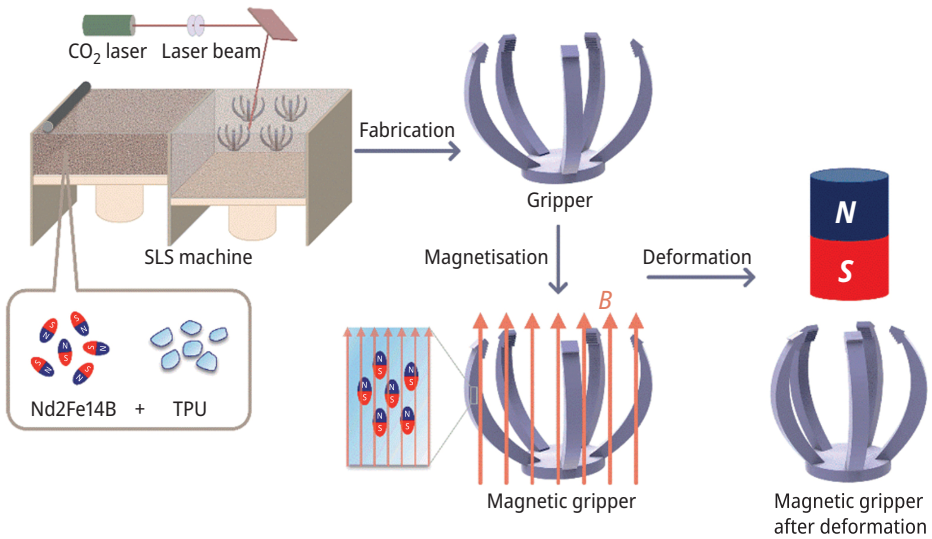


Fig. 8.4: Schematic of the SLS process and magnetization process to fabricate the gripper to deform under the external magnetic field [41].

8.3.3 4D printing by SLA

Another technique has been utilized to create 4D-printed model is SLA. Although SLA is primarily a 3D printing method, it can also serve as a foundation for 4D printing by incorporating SMPs into the process [44]. SLA utilizes a vat of liquid resin that is solidified layer by layer using a focused UV laser. This results in the gradual creation of a 3D object. By integrating SMPs into the SLA process, these printed objects acquire the capability to alter their shape or properties when exposed to specific triggers. The SLA process has benefits such as smooth surface finish, quick speed, and high resolution. SLA can print products with improved surface finishes compared to usual machine and addition to products with more complex geometric designs [45]. Functional materials for SLA technology have been created due to the continual advancement of technology. For instance, smart materials with excellent shape-memory performance were created for SLA and printed microstructures [46].

SLA can print parts from polymer materials; however, the finished products have poor mechanical qualities. The need for a support system, which necessitates post-processing and long response times, are drawbacks of SLA. In soft robotics, biomedical scaffolds, drug delivery, and tissue engineering, numerous studies have used SLA [47, 48]. SMPs based on the phase-switching mechanism were printed by Choong et al. [49] using SLA. This printed SMP exhibits shape-memory behavior and could be unfolded after printing at 25 °C and regaining its original buck-ball shape by soaking in water heated to 65 °C as shown in Fig. 8.5. In the other study, Zhao et al. [45] created a kind of UV-curing

prepolymer of polyurethane that was used to develop products utilizing SLA. Temperatures in a water bath are indissolubly linked to the recovery angle of microstructures.

A temperature-responsive polymer created from NVCL samples manufactured via SLA and UV chamber polymerization allowed for completing 4D printing [46]. According to the study's findings, the NVCL-based polymer was successful in realizing the practical 4D printing concept. This provides new material for 4D printing research and the opportunity to use NVCL in a new area beyond biomedical applications. The primary focus of study in magnetism-driven 4D printing using SLA of liquid photosensitive materials is the deformation of composite materials made of magnetism-responsive polymers, accomplished by AM procedures.

Micro-SLA, another SLA method, forms a tiny layer (1–10 mm thickness) using an ultraviolet (UV) laser beam [33, 50]. Numerous applications, including forming deployable aeronautical structures and multimaterial SMP devices, have benefited from using micro-SLA [51].

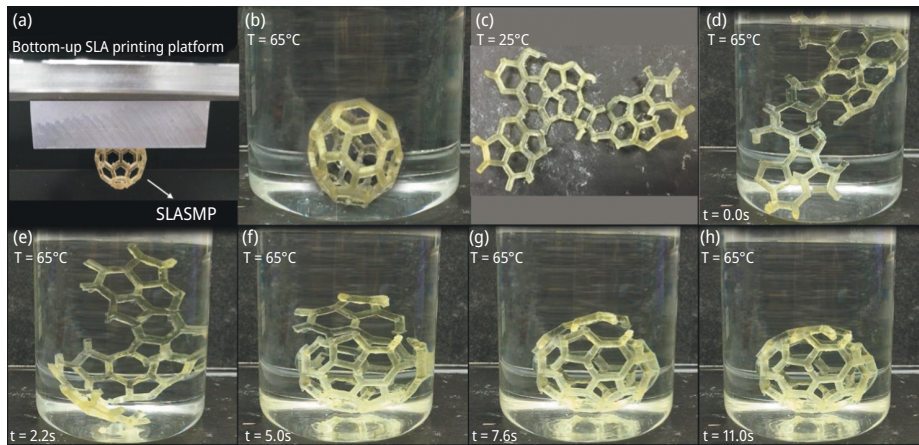


Fig. 8.5: (a) SLA SMP in printing, (b–c) unfolded condition, and (d–h) recovered its original bucky-ball shape by soaking at 65 °C of water [49].

8.3.4 4D printing by DIW

The most popular 4DP technique is DIW, followed by FDM method. Unlike traditional 3D printing methods that use filament or powdered materials, DIW allows for the deposition of a wide range of materials, including polymers, ceramics, metals, and even biological substances. The ink or material is typically loaded into a syringe or a similar reservoir, and it is pushed through the nozzle using pneumatic or mechanical means [52]. The movement of the nozzle is controlled by computer-aided design software, allowing for precise control over the printing process [53, 54]. Direct ink print-

ing allows for the creation of intricate patterns or designs on different surfaces, opening up possibilities for applications like flexible electronics, wearable devices, or even biomedical implants [55]. DIW offers several advantages, including the ability to print complex geometries with high resolution and customization. For instance, DIW has been used to print biodegradable scaffolds [56] and highly flexible self-healing shape-memory elastomers [57]. These elastomers capacity for self-healing has the potential to revolutionize biomedicine.

Their integration of smart materials with DIW techniques enables the printing of complex structures with embedded functionality and responsive properties. DIW is successfully used to print alkali-activated pastes starting from refractory wastes. In particular, two different aluminosilicates raw powders (chamotte and alumina-zirconia-silica) were used. DIW was employed effectively to produce 3D-printed samples from refractory wastes based on alkali-activated pastes that had good mechanical strength and the capacity to withstand high temperatures [58]. To develop underwater acoustic transducers, researchers have explored the synergistic use of piezoelectric material PZT and DIW technique. Through testing the performance of piezoelectric composites with varying rod spacing, optimal combinations have been identified for the production of 4D components [52]. The underwater acoustic transducer's electrical signal altered in response to auditory stimulation, indicating a potential use for 4D printing in creating practical objects in the future.

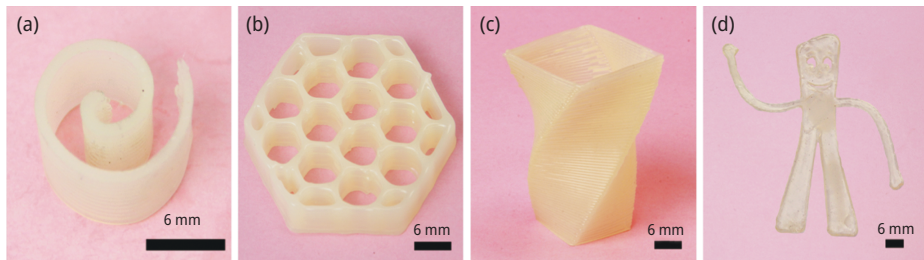


Fig. 8.6: UV-assisted DIW-based 3D printed samples: (a) Archimedean spiral, (b) honeycomb, (c) hollow vase, and (d) Gumby toy [59].

The DIW-based 3D printing technique was used to fabricate Archimedean spiral, honeycomb, hollow vase, and Gumby toy in semi-IPN elastomer composites for the investigation (Fig. 8.6a–d). The complex structures produced through 3D printing exhibit intriguing functional properties, including the ability to undergo high strain deformation and self-healing facilitated by smart materials. This study opens possibilities for advanced soft robotics, 4D printing, and biomedical devices [59].

Uchida and Onoe [60] introduced a novel fabrication technique for 4D printing, as illustrated in Fig. 8.7. This method enables the creation of 3D multihydrogel structures with internal gaps. 4D designs are created by printing a stimuli-responsive pre-

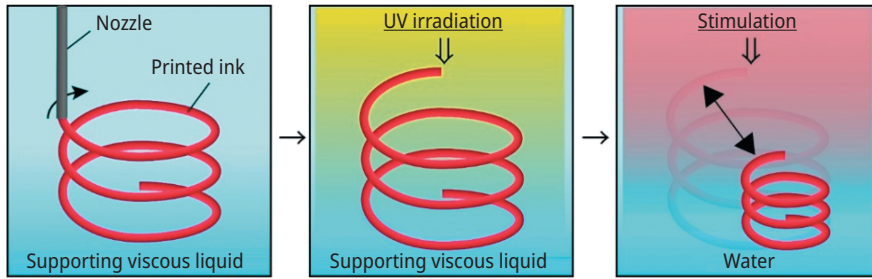


Fig. 8.7: 4D structure with internal gaps with multiple functions fabricated by DIW techniques [60].

gel solution based on *N*-isopropyl acrylamide, along with an unresponsive pre-gel solution, within a viscous liquid serving as a support medium. The print designs are then polymerized using UV light irradiation.

8.4 Summary and conclusion

- 4D printing, a fast expanding field that combines 3D printing principles with the temporal dimension to allow printed items to change over time in terms of shape, property, or functionality. Research on 4D printing and smart materials is expanding the capacity of current manufacturing processes, bringing up a world of innovation that has a chance to revolutionize a number of industries.
- Different smart materials, or an assortment of smart and conventional materials, can be used to create multimaterial 4D structures that can dynamically change their shape over time in response to external stimuli.
- The most often used 3D printing techniques in 4D printing are FDM and DIW. Using specifically engineered polymers, FDM and SLS develop resin-based systems that can create flexible to rigid structures.
- In 4D printing, there is still a need to optimize the biocomposite formulation by modifying the interfacial bond strength and selecting appropriate fibers and matrices to improve actuation performance, particularly in terms of durability.
- The capacity to change shape or take on different forms is widely desired in a range of applications, including soft robotics and the biomedical industry. Magnetoactive polymeric structures created by 4D printing display enormous potential for these applications.
- The construction of dynamic and responsive structures is made possible by 4D printing processes, which will ultimately improve the capabilities and use of smart materials in the future.

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9 A comprehensive review on effect of DMLS process parameters and post-processing on quality of product in biomedical field

Abstract: As a result of its ideal combination of strength, malleability, and corrosion resistance, stainless steel is frequently utilized in additive manufacturing (AM). There are a range of applications from mechanical to bioengineering for stainless steel 316L. Components made of SS316L that are additively manufactured provide geometric accuracy and homogeneity in properties. In spite of the fact that various studies have been conducted on the manufacture of 316SS parts by AM processes, such as laser powder bed fusion (LPBF), there is ample scope for enhancing mechanical properties of the parts by applying a proper post-processing technique after manufacture. As a part of this chapter, we have taken an in-depth look into process parameters involved in the direct metal laser sintering (DMLS) process, their impact on product quality, and post-processes in order to enhance properties. An overview of AM applications in biomedical field and implant development using SS316L is presented in this review. When thermal treatment is applied and the optimal parameters of manufacturing are selected, overall ductility and elongation can be improved. Compared to printed samples, components were more ductile after post-processing. Furthermore, heat treatment results in homogenized microstructures and reduces residual stress. By heat-treating metals, corrosion resistance and wear rates have both been increased.

Keywords: DMLS, post-processing, mechanical properties, biomedical application

9.1 Introduction

The process of additive manufacturing involves joining layers of material using digital 3D models. The availability of models allows for better resource allocation, resulting in less waste during the manufacturing process. Application-based material development is facilitated by the use of additive manufacturing (AM). The most significant feature of laser powder bed fusion (LPBF) is how well it can handle complex geometries and with a greater level of precision [1–3]. Material integration improves performance and durability by improving the efficiency of the models [4]. While numerous studies have already been conducted in this area, some gaps remain in terms of mate-

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materials' reduced ductility and elongation, making them less efficient. Furthermore, different researchers have not looked at the deformation mechanisms under different loading conditions.

Since LPBF works better with complex geometries and with more precision, it is the most often utilized kind of AM. LPBF can fuse steels, aluminum alloys, chromium, and other metal powders. The models become more efficient and durable as a result of the proper integration of materials. It is possible to melt or partially melt the metal powder using laser power, and subsequent layers are added and fused to form a single item using powder bed technology (direct energy deposition and powder bed fusion (PBF)) [5]. Solid-state sintering, chemically driven binding, liquid phase sintering (partial melting), and full melting are all examples of binding mechanisms in this process. Classification of additive manufacturing techniques and PBF process subtypes are shown in Fig. 9.1 [6].

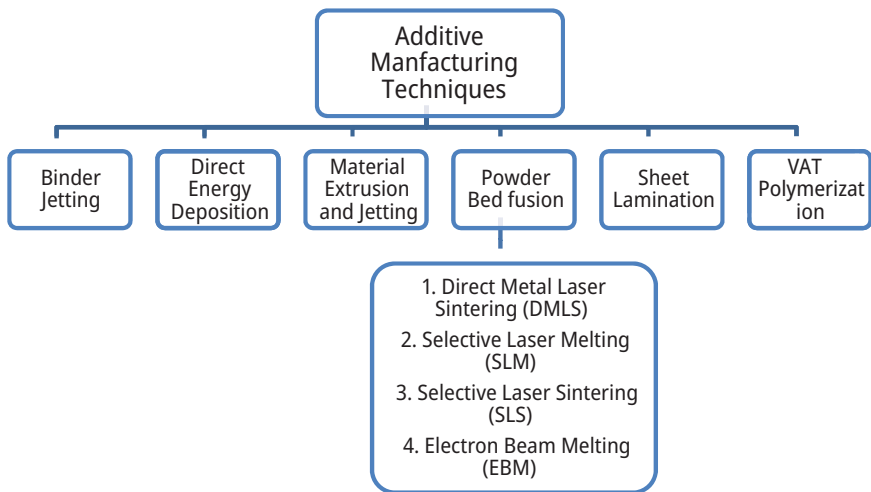


Fig. 9.1: Classification of AM technologies.

Complex geometries can be produced by additive manufacturing with acceptable properties [7]. LPBF involves several process parameters that influence the final product's properties. However, despite PBF having fundamentally evolved and being used in a wide range of enterprises, there are still significant difficulties and issues associated with the system. Cycle repeatability, process consistency, and cycle solidity are affected by these difficulties [8]. Several exploration works have examined the impact of operation boundaries on output for a range of materials and machines; however, it has been difficult to assess the aggregate impact of the relative multitude of boundaries on the properties of a manufactured part.

Some of the major parameters involved in the process are mentioned in Fig. 9.2. Since AM parts are made from high-intensity energy-based melting processes, they exhibit poor surface quality and high residual stress, which affect mechanical properties and surface integrity. In AM products, porosity and residual stresses are the most common defects, which can be minimized by optimizing process parameters and using the right post-processing techniques. The use of additive manufacturing is most suitable for small-volume products with complicated geometries that are difficult to machine with conventional machining processes. In addition to reducing material waste and tooling requirements, AM also reduces overall cost and skill requirements for custom-made components with complex geometry. In addition to the equipment cost, a limited number of materials are available, and post-processing is required for refinement of properties [9, 10].

Modern-day AM is becoming popular and is finding application in the medical field for the development of physical models of body parts. This includes biomodeling, tissue engineering, microscale medical devices for drug delivery, orthopedics for implant development, and surgical tool development. These parts are manufactured by reverse engineering. In this process, a part is scanned and the obtained 2D image is used for developing a 3D model, which is then used for printing [11, 12]. 3DP can produce organs and porous bone scaffolds, depending on the anatomy of a patient, from bio-inks such as gelatin, alginate, and agarose to ceramics, polymers, and different biomaterials. This review focuses on the direct metal laser sintering (DMLS) process for 3DP and how its parameters affect product quality in the product development process.

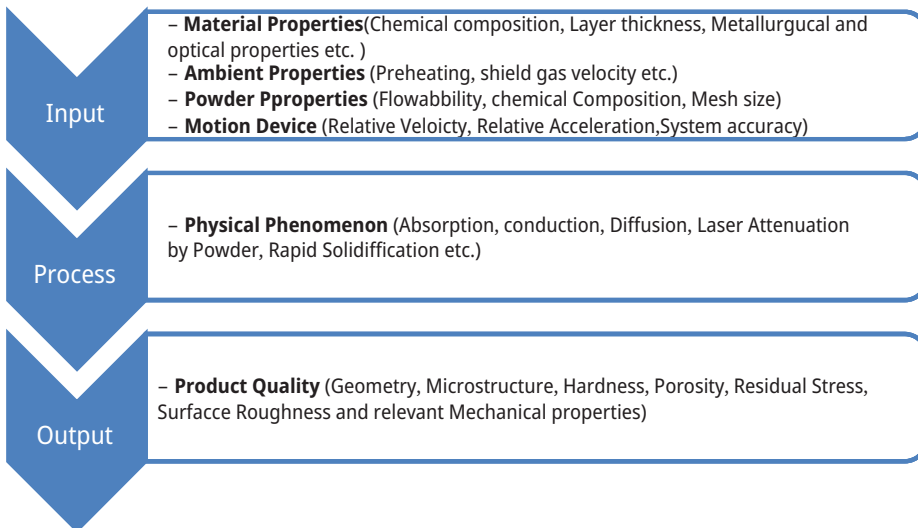


Fig. 9.2: Process design parameters for LPBF.

In order to minimize defects in PLF-printed parts, the parameters mentioned above must be optimally selected and post-processing heat treatment (HT) must be performed. Build orientation is another significant factor in deciding the isotropy of material [13, 14].

9.2 Biomedical field applications

The number of bone fractures in India is estimated to be around 20 million per year. The growth rate for bone replacement due to aging, fractures, and other diseases related to bones is projected to be the highest from 2020 to 2026. It is crucial to select materials for implant preparation with high biocompatibility and biodegradability for treating bone defects. Strength, corrosion resistance, biocompatibility, wear resistance, and biocompatibility are some of the key material characteristics that must be taken into account when selecting a material. Printed objects are obtained at the near net shape and this process takes very less time for implant development. AM produces implants with improved strength, superior finishing, and capable of handling complicated shapes reducing overall operation time which is beneficial for patients as well as doctors [15–17]. Merits and limitations of AM from the prospective of the biomedical field are summarized in Fig. 9.3.

The materials that can be processed by acellular AM techniques include titanium, titanium alloys, CoCrMo alloys, surgical grades of stainless steel 316, tantalum, and niobium. Materials such as SS 316L, which is used to manufacture nails, screws, and plates in biomedical applications, have been extensively investigated in this field. Dental and orthopedic implants, such as hip joints and knee joints, are made using AM. Three types of implants exist based on the number of cellular components included in them: biological implants, biologized implants, and bio-functional implants. AM has the potential to be used in the creation of implantable medical devices for humans. Since every patient has a unique anatomy, customized implants are necessary to match individual needs. An implant mimicking natural bone structure can be produced from 3D printing, using CAD, which generates a stereolithography model for 3D printing. General steps followed in implant development are shown in Fig. 9.4. Study results have shown satisfactory results in both in vitro and in vivo testing of DMLS-manufactured implants in humans and animals [18].

There are a number of factors that contribute to the failure of implants, such as corrosion, fatigue, and wear. It is very important for an artificial implant to integrate with the surrounding bone during the healing process. This is called osseointegration [19]. Researchers, medical experts, and manufacturing engineers find AM promising because it can produce parts with delicate internal structures, dense as well as porous parts, and complex geometries in one run without using specialized tools. Surgeons' skill and the type of equipment available are significant factors in the success of some surgeries, especially those involving the neural system. The use of biomodeling can

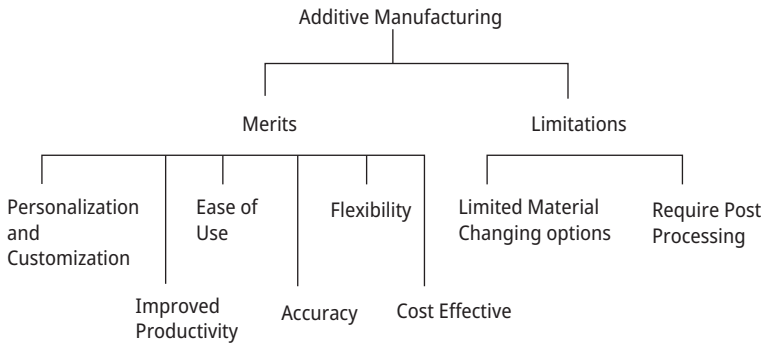


Fig. 9.3: The merits and limitations of AM from the perspective of the biomedical field.

assist neurosurgeons in cases where an exact model is reproduced and virtual surgery can be performed. This increases the success rate of such critical operations. The only limitation of AM in the biomedical field is to obtain better surface and mechanical properties of the produced implant [19, 20]. There are two causes of corrosion in steel implants: the first is oxidation and reduction in the environment and the second is the formation of oxide layers. In the event of deformation, these oxide layers begin to react with the environment and deteriorate over time. Layers of oxide exhibit this

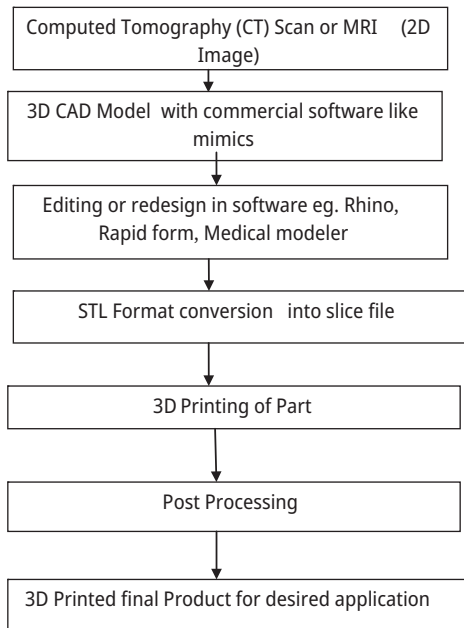


Fig. 9.4: Process flow for developing additive manufacturing of implant.

trait, which is referred to as passive behavior. Human body fluids must have a stable oxide layer in order to prevent corrosion.

9.3 DMLS process and nomenclature

The DMLS process uses a high-power laser to fuse micron-size powder particles into solid parts within a short time frame based on a computer-generated 3D model. Besides nonmetallic materials, this process is also applicable to polymers and metal powders with different alloying elements and melting points. The powder particles are not melted in DMLS, but sintered to a temperature where they become welded together and solidify. This process uses raw material in the range of 20–40 μm and particle morphology, that is, particle size and evenness in particle size, is among the major factors influencing the product quality [21].

The DMLS process involves moving and focusing laser beams over a small layer of powder in order to create the intended shape of the end product. The conceptual construction of the DMLS process is shown in Fig. 9.5. The laser's heat energy fuses the particles together, resulting in a solid layer of powder. The process is repeated with a second layer of powder, allowing both layers to be cemented together. Powder particles are sintered in an atmosphere of inert gas control, most commonly Argon [22, 23]. When recoater blades move across platforms, they spread powder evenly equal to one layer thickness and collect surplus powder. The building and collection platforms are lowered by the same amount of one layer thickness. This process of product development inside the chamber has been represented in the form of flow diagram in Fig. 9.6. When printing inclined portions of an object, a properly designed support structure is crucial to preventing distortion, particularly at more than 40° of inclination. A vacuum cleaner is used to remove excess powder from the chamber after the final printed part is removed from the printer for post-processing [24]. A sieve is used to clean the used powder before recycling it for new production. Recycled powder has been found to produce higher surface roughness values when compared with new powder in research conducted on part quality. According to a study of the particle morphology of reused powder, previous partial melting produced larger, less spherical particles [25].

It processes a variety of materials, including titanium and titanium alloys, aluminum and aluminum alloys, steel (SS304, SS316L), Inconel 718, Co–Cr alloy, and others. The parts made by DMLS are used in a wide range of fields, such as implant development, aerospace, and automotive. Currently, investigations are being conducted regarding the selection of process parameters and ways to reduce defect levels in DMLS components. Table 9.1 illustrates the element composition of different grades of stainless steel materials processed by DMLS.

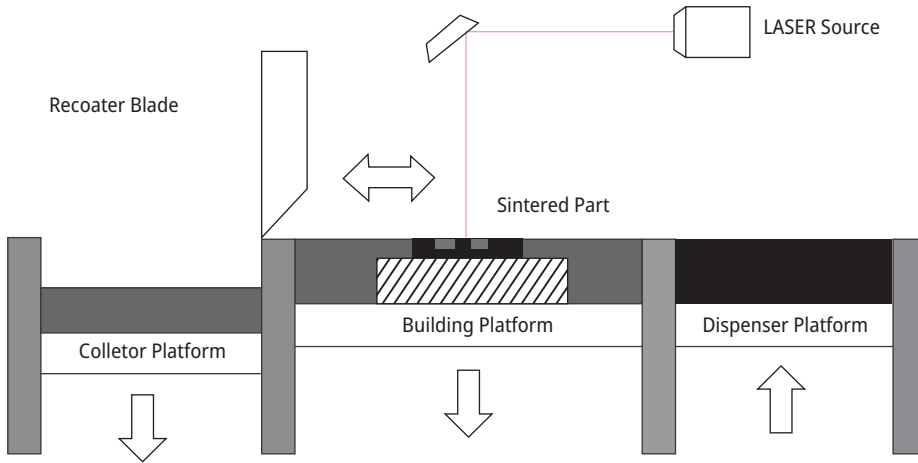


Fig. 9.5: Conceptual representation of DMLS process.

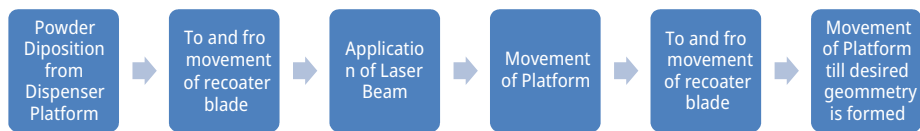


Fig. 9.6: Process flow diagram for DMLS (inside chamber).

Tab. 9.1: Material composition of DMLS process materials.

Material ↓ Component	316L	17-4 PH SS	CoCrMo powder	IN 718
C	0.03	0.07	0.15	0.08
Cr	Max 18	15-17.5	29.4	17-21
Fe	62	–	0.26	–
Mn	2	1	0.75	0.35 max
Mo	Max 3	–	6	2.8-3.3
Ni	Max 14	3-5	–	50-55
P	0.045	0.04	–	0.015 max
S	0.03	0.03	–	0.015 max
Si	1	1	0.08	0.35 max

9.3.1 Process parameters

A discussion of major process parameters and their significance in the DMLS process is presented in this section. In this context, laser power and material parameters as shown in Fig. 9.8 have been discussed despite the fact that there are several parameters involved in process design. Process parameters are mainly grouped into two categories viz. laser-related and material-related. It is estimated that there are over a hundred parameters involved in the AM process. Laser control parameters include laser power, laser spot diameter, hatch spacing, and scan speed [26, 27]. Material-related parameters include layer thickness, powder particles size, and alloy content in powder. AM part defects are influenced by the choice of these parameters, thus affecting the final product quality. This section discusses the major parameters involved in the DMLS process.

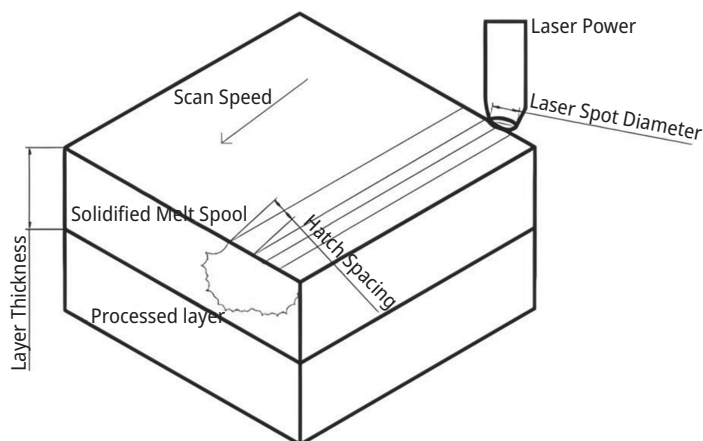


Fig. 9.7: DMLS process parameter nomenclature.

The following section discusses major process parameters and their significance in the DMLS process. Though there are many parameters involved in process design here scope of discussion has been limited to parameters related to laser power and material as mentioned in Fig. 9.7.

9.3.1.1 Laser beam spot size (d)

It is the diameter of a laser beam incident on the powder layer. Porosity in AM parts increases as laser beam spot size decreases as a smaller spot size irradiates less area. Reported research indicates that laser beam spot size affects porosity.

9.3.1.2 Hatch spacing

It is a parallel distance between successive layer tracks. The surface roughness of the build is influenced by it, along with the build quality and the build time as well. Hatch overlap ratio (d/h) occurs when spot diameter is more than hatch spacing. The process results in remelting of layers and helps to obtain a superior densification and surface finish. Higher hatch spacing reduces total scan lines, resulting in insufficient bonding. With less hatch spacing, laser scan tracks overlap, resulting in remelting of layers and a dense structure [28].

9.3.1.3 Scan speed (v)

It is the speed at which the laser beam is moved over the powder layer. Scanning speeds is a function of surface roughness, build time, and required material properties. Insufficient bonding between subsequent layers is observed as high scan speeds reduce penetration depth as exposure time is also reduced. Conversely, slower scan speeds increase build time and increase microhardness by forming a less porous structure [28].

9.3.1.4 Layer thickness (t)

The thickness of the powder coating spread by a recoater blade. Among the most important factors are the powder particle size and the power of the laser. Based on the thickness of the layer, the amount of energy needed to melt the powder varies. When the layer thickness is greater, more gases are trapped within the powder, and they must travel a longer distance to escape. Porosity and strength are decreased as a result of the remaining gases that form pores in the layer [29, 30].

9.3.1.5 Laser power (P)

It is the intensity of the laser beam. High laser power provides better strength to the component, but also creates more roughness. As a result of high laser power, the metal powder melts and a high amount of vapor pressure develops, causing small holes to form [31]. Having low laser power provides less heat energy at contact, and scanning at high speeds results in less dense structures. Laser power also influences the cooling rate, T (K/s), represented by the formula [32]:

$$\lambda = 80 \times T^{-0.33} \quad (9.1)$$

In the case of high laser power, the cooling rate is slower. This allows growth in the preferred crystallographic orientation. However, when the laser power is lower, the cooling rate is faster, resulting in a fine cellular structure. In recent research laser power value ranges from 30 to 1,200 W, thus indicating a need for optimization of laser power values for different materials.

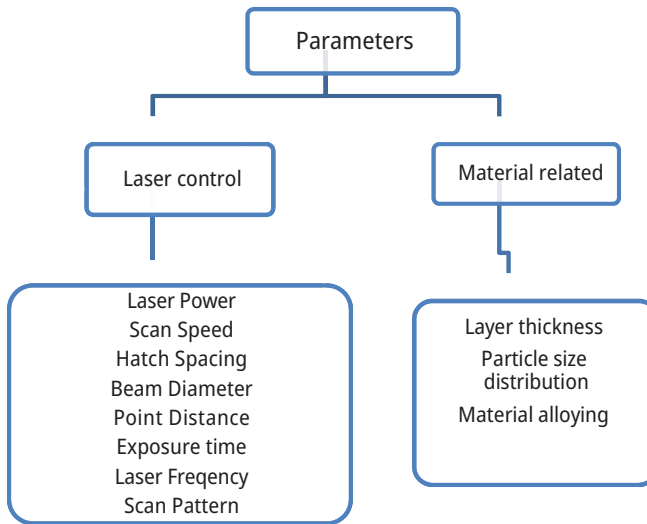


Fig. 9.8: DMLS process parameters.

9.3.1.6 Scan pattern

It is the path through which laser is moved over powder bed. Apart from the standard partition approach, oblique line and spiral line scanning strategies are also available. Different types of scan strategies used for DMLS process have been shown in Fig. 9.9. Spiral line strategy has been found to be most suitable for improving properties and producing parts with almost 99% density [33–35]. Selection of scan strategy depends on scan speed and material. Once a final product's geometry has been finalized, it is divided into islands. A raster scan is carried out on the periphery of these islands. Counter scans are performed within this periphery [36, 37]. In order to reduce the likelihood of developing porosity caused by the balling effect, scanning tracks should be overlapped purposefully so that the surface is smoother and less likely to develop porosity.

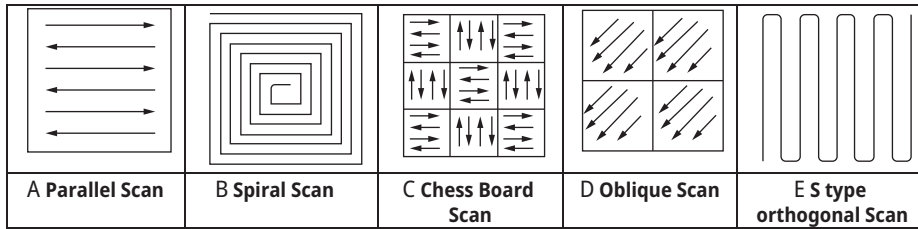


Fig. 9.9: Different scanning strategies.

Tab. 9.2: Process parameter combinations by various researchers for SS 316L for SLM process [38].

Laser power, P (W)	Scan speed, v (mm/s)	Layer thickness, t (mm)	Hatch spacing, h (mm)	Volumetric laser energy density, E_v (J/mm ³)
500–1,800	150–400	0.030	0.150	28–74
190	800	0.050	0.150	32
50–100	300–1,250	0.030	0.070–0.140	32–80
200	1,600	0.050	0.060	42°
100–200	200–220	0.050	0.124	81–150
100–150	700	0.020	0.050–0.070	102–214
200	400	0.040	0.080	156
120–190	300–900	0.08–0.012		58–166

9.3.1.7 Building direction

Building directions change mechanical properties, which are influenced by the microstructure [39]. A comparison of samples built vertically, horizontally, or at 45° has revealed that samples built horizontally have superior mechanical and tribological properties than samples built vertically or at 45° [40–42]. Figure 9.10 shows specimens with vertical and horizontal build directions. It was found that specimens that were vertically constructed had both large equiaxed and small columnar grains, whereas specimens that were horizontally constructed had large columnar grains. Specimens with 45° angles had grains that were nearly equiaxed.

There has been considerable variation in the magnitude of process parameters discussed in this section. Table 9.2 presents some of the parameters adopted by the researchers.

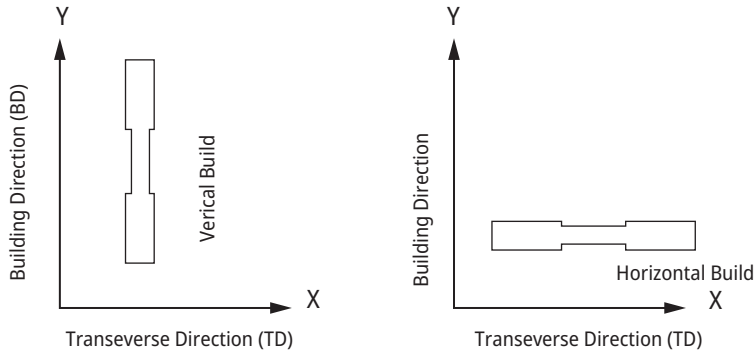


Fig. 9.10: Building direction.

9.3.1.8 Volumetric energy density (VED)

As a measure of energy input per unit volume, it is closely linked to surface roughness. VED is represented as

$$VED = \frac{P}{v \cdot h \cdot t} \quad (9.2)$$

VED is a common term that represents the effect of four process parameters on surface quality. When the VED is higher, the melt pool behaves more unstable, which causes more spatter, and when it is lower, less energy is provided for sintering and the surface becomes rough. Aside from laser power and scan speed, material volume is also a factor affecting energy consumption in the AM process. A higher VED can also lead to keyhole defects that are detrimental to mechanical properties. A deeper, narrow melt pool is formed when VED is high, resulting in the melting and evaporation of powder particles. The vapors formed in such cases cannot escape out of the melt pool before solidification, creating a keyhole defect that affects mechanical properties [43]. By changing laser power, hatch spacing, or scanning speed, the energy density is influenced, which greatly influences melt pool shape, cooling rate, and microstructure.

9.3.1.9 Material-related parameters

There are several factors that relate to the material, including the particle size of the powder and the alloying constituents. Gas atomized powder is usually preferred over water atomized (WA) powder. As a result of the interlocked particles in WA powder, the flowability is reduced. GA powder particles have a better flowability and are almost spherical in shape. The flowability of the powder layer plays an important role

when spreading it on the bed [44–46]. Alloying elements Ni and Cr are responsible for corrosion resistance, while C and Mo are responsible for mechanical properties. The material powder consists of primary particles, aggregates, and agglomerates. A primary particle is one that cannot be separated from another; this is why they are referred to as fundamental particles [47, 48]. Aggregates are formed when primary particles fuse by sintering or pressure. The handling, rolling, or storage of powder particles undisturbed for a long period of time causes loose bonds between the particles, which leads to the formation of agglomerates. Proper dispersion techniques can separate these particles.

9.3.2 Defects in the DMLS product

In the DMLS process, the quality of the product is determined by factors including laser power, hatch spacing, layer thickness, laser beam spot size, scan speed, and building direction. Our goal in this part is to determine what effect the parameter values have on the mechanical and tribological properties of the product. The various processing parameters and characteristics of feedstock determine the defects in components manufactured by LPBF. A number of defects can be found in these materials, such as surface roughness, balling, lack-of-fusion pores, gas porosity, gaps/voids, keyhole pores, macro and micro cracks, and residual stresses. Porosity, staircase effects, balling defects, and other defects should be minimized by selecting process parameters optimally. An overview of the defects that result from poor parameter selection in additive manufacturing is presented in order to illustrate how improper parameter selection leads to defects in AM products. Though these defects are not eliminated their effect can be minimized by optimal parameter selection and post-processing [49, 50]:

- a. Balling defect
 - b. Staircase defect
 - c. Porosity
- a) Balling defect: Balling defect in DMLS is a major impediment to achieving desirable properties and it arises due to improper selection of process parameter values. Two kinds of balling defects have been observed: the first kind of balling defect has been observed due to less laser power, and the second kind of balling defect is due to high scan speed. Increase the density of the powder coating or reduce its thickness to minimize this fault [51–53].
 - b) Stair stepping effect: In AM, a product is developed by adding material layer by layer, and due to the layered nature of this process a wave pattern develops on the outer surface of a developed part. This results in a low quality surface. This effect is more noticeable on inclined or curved surfaces. It is possible to minimize this defect by adjusting layer thicknesses, changing the building direction, and using post-processing techniques [54].

- c) **Porosity:** The porosity of a material depends on several parameters, including the VED and particle size. The high scan speed, low laser power, or the thick layer that results in a low VED cause the particle partial melting. This results in voids inside the formed layer. In consequence, the product is less dense and has a low strength. Additionally, pores can be a source of crack formation in AM parts and reduce their fatigue life. These defects in AM have been shown in Fig. 9.11. The density of AM products ranges from 94% to 99% with post-processing in some cases [55].

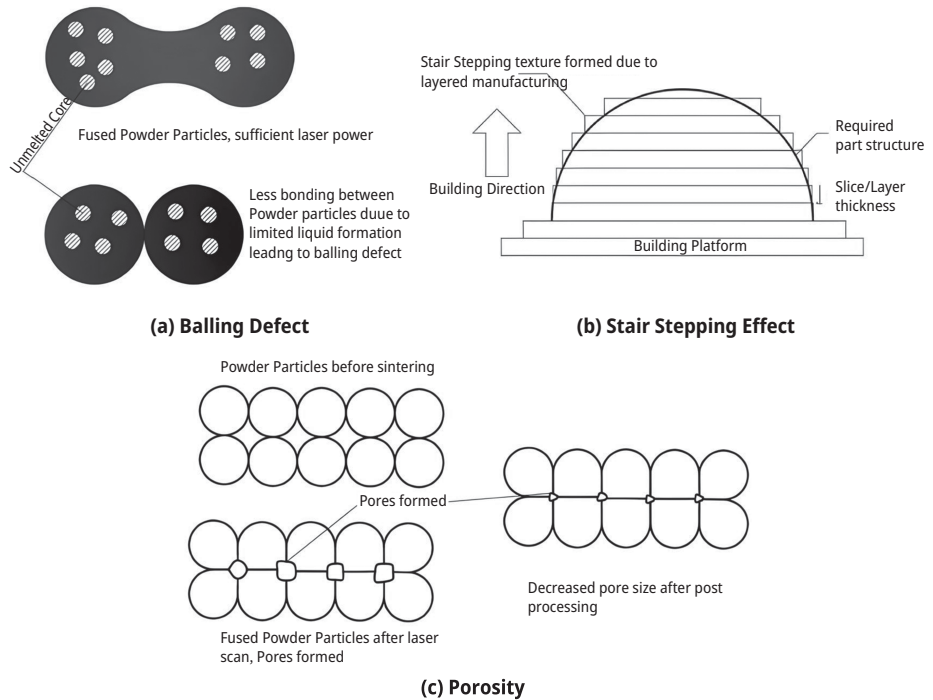


Fig. 9.11: Defects in AM.

During PBF, two types of pores form: spherical pores are formed by the gas encapsulated in the powder, whereas keyholes result from insufficient optimization of processing parameters like laser beam power and scan speed. A trapped argon gas in the powder during the atomization process sometimes causes DMLS printed parts to have inherent pores. In the case of low laser power, these inherent pores are more apparent. Pores formed in the AM process are spherical in shape. Sphericity is the term used as a measure of the spherical shape of pores. Mathematically, it is represented by the formula:

$$S = \frac{\pi^{\frac{1}{3}} \times (6V)^{\frac{2}{3}}}{A}$$

where S is sphericity, V is the volume of the pore, and A is the surface area of a pore. Porosity depends on the shape of powder particles whether they are spherically or nonspherically shaped.

The porosity of AM parts is calculated by using Archimedes technique. The density of manufactured samples is calculated using the following formula:

$$\rho_{\text{experimental}} = \frac{m_a}{m_a - m_w} \times \rho_w$$

where m_a and m_w are masses of manufactured samples in air and water, respectively. These masses are measured using an electronic balance. $\rho_{\text{experimental}}$ is the density of manufactured samples and ρ_w is the density of water.

Porosity is calculated from the difference in theoretical and experimental density values using the following formula:

$$\text{Porosity (\%)} = \left(\frac{\rho_{\text{Theory}} - \rho_{\text{experimental}}}{\rho_{\text{Theory}}} \right) \times 100$$

9.4 Post-processing

9.4.1 Heat treatment

Post-processing treatments such as HT enhance physical and mechanical properties by adopting a homogenized microstructure. Mechanical strength is improved by the cellular structure, and its disappearance affected the strength drastically. Only grains remained after the HT destroyed the LPBF-316L specimen's cellular structure and melt pool boundaries. In comparison with the as-printed specimen, the heat-treated LPBF-316L specimen shows adverse mechanical properties, including yield strength, ultimate tensile strength, and microhardness. A key defect in AM is porosity, which can be reduced but not eliminated by optimizing parameters. The purpose of HT is to reduce the stresses formed during the AM process, as well as to reduce the porosity in the material, thereby improving its mechanical and microstructural properties. Cracks caused by small pores in AM components can negatively affect their mechanical strength. Microstructure can be refined through HT to minimize the effects of porosity. Prior research has treated as printed samples with annealing, hot isotactic pressing (HIP), and cryogenic HTs. As a result of this research, the porosity of the material has been reduced, resulting in better strength and hardness values for the material. Compared to other HT processes, HIP and annealing yield better strength and other properties. In addition to

reducing residual stress, HT also homogenizes the microstructure of as-printed samples [56]. A higher temperature may alter the material's microstructure and increase the ductility, which leads to a reduction in strength. With HT, the ferrite phase reduces and leads to an increase in ductility. Furthermore, heat-treated samples have shown increased corrosion and wear resistance when compared with as-printed samples [57–59]. When post-AM HT is employed to release residual stress, particularly at temperatures higher than 1,000 °C, detrimental inclusions and precipitates may appear, reducing corrosion resistance against pitting. A solid-state grain refinement process is a better alternative to HT, as it improves strength and ductility.

9.4.2 Mechanical post-processing

A post-processing step can involve the removal of materials, the improvement of surface texture and aesthetics, the separation of components, the debinding and sintering of parts, the machining of parts, the finishing of surfaces, the enhancement of nonthermal properties, HT, and quality checks. AM parts are subjected to residual stresses as a result of the sintering of powder particles, and these residual stresses are relieved through shot peening and shot blasting. These post-processes result in the refinement of surface grains yielding better corrosion resistance. Printed samples have needle-like structures on their outer surfaces, resulting in higher roughness values. A shot peening process also removes these irregularities and improves the surface finish. The effect of shot peening on surface roughness has been shown in Fig. 9.12. In some cases, HT results in martensite, which causes the material to become more brittle. The outer surface of a shot peened component has been observed to harden after strain hardening during shot peening [60–62].

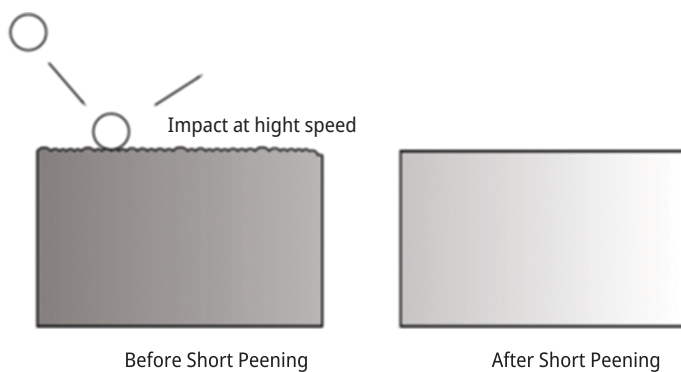


Fig. 9.12: Shot peening process.

9.4.3 Surface coating

Various surface coatings are applied on AM parts by cold spraying or hot thermal spraying to improve their corrosion resistance, wear rate, surface roughness, and hardness. Orthopedic implants can benefit from this treatment because it enhances osteointegration. Study results show that cold-sprayed surfaces increase the fatigue life of AM components. When it comes to improving surface roughness, grinding and polishing with emery are thought to be the most effective option that can produce a surface with less than a 1 μm roughness value. Based on the substrate material and desired property enhancement, some of the coating materials include PTFE, CrN/NbN coating, Ni, and Al alloy [63–65].

9.4.4 Hot isostatic pressing (HIP)

Hot isostatic pressing is applied to DMLS printed parts after HT to obtain a more dense structure and residual stress removal. Sintered parts are subjected to high temperatures and high pressure in the HIP, which gives them almost 100% density and a refined microstructure. Gas and liquid mediums are used for transmitting pressure in this process. As a pressure-transmitting medium, argon gas is mostly used. There are three variables involved in this process: pressure, temperature, and time. A schematic representation of this process is shown in Fig. 9.13. It is imperative that the above-mentioned process parameters are controlled properly in order for this process to be effective. Since pores which act as stress concentration sources are eliminated by the HIP, the fatigue life of the component is improved [58]. The combination of hot post-treatments and HIPs is an effective method for treating keyhole defects. With HIP, the porosity of DMLS-produced 316L SS is significantly reduced and the microstructure is homogenized, thereby increasing pitting corrosion resistance [66].

9.5 Mechanical and tribological properties

Researchers have developed rectangular samples to evaluate mechanical properties and also the effects of HT in order to analyze the properties and process parameters. A list of the various mechanical and tribological tests conducted on AM components is shown in Fig. 9.14 [67, 68]. The process of additive manufacturing makes it possible to produce complex shape geometries from variety of materials in a short amount of time using CAD data. The most popular technique for manufacturing parts by additive manufacturing is LPBF. The quality of the final product manufactured by DMLS depends on various process parameters viz. laser power, hatch spacing, layer thickness, scan speed, beam size, etc. It is worth noting that some parameters are more significant than others when it comes to determining the quality of a product. Quality of product

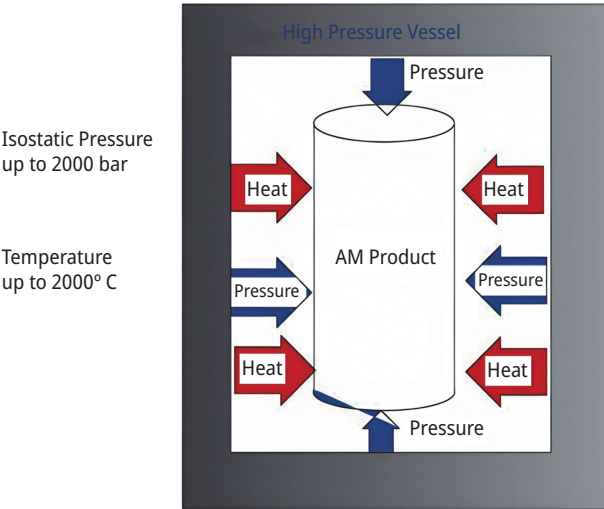


Fig. 9.13: Schematic representation of HIP.

refers to the mechanical and tribological properties which include tensile strength, hardness, porosity, and surface roughness. Table 9.3 shows the correlation between process parameters and material properties [69, 70].

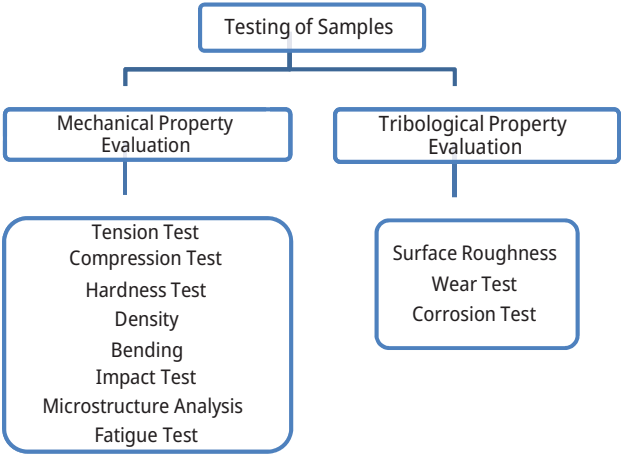


Fig. 9.14: Mechanical and tribological property evaluation of AM part.

It is critical from the standpoint of a biomedical application to ensure that surface properties such as wear resistance and corrosion resistance are present. Surface con-

ditions of biomedical components determine the life and function of implants, such as heart valves, dental crowns, arthritic joints, and knees. As a result of the actions taken by the body, such as walking, running, and cycling, the implants have to sustain different loads. A result of the movement between the implant and different bone parts leads to the wear of the outer surface as well as the accumulation of debris around the implant. In addition to surface irregularities and poor wear resistance, surface irregularities also affect impact strength and fatigue life [71]. In order to improve these surface properties, post-processing is performed on AM components. Several surface enhancement techniques have been found to be successful for enhancing surface properties, such as shot peening, coatings, and HTs. Stainless steel 316L implants are treated as temporary in the human body, which makes corrosion resistance a vital factor when choosing implant materials. Enhancing the corrosion resistance of SS316L is a major hurdle faced by researchers today. As a result of high acidity levels in body fluids, implants made from SS316L have a life expectancy of a few months to a maximum of seven years. Human body fluids normally have a pH value of 7. Medications and diseases can alter pH levels, causing body fluids to become acidic, which can lead to early implant failure, which can reduce its lifespan.

The evaluation of microstructure is crucial to the assessment of mechanical properties; dislocation density and grain size determine the strength of the component. Porousness, residual stress, and strength of a component are greatly influenced by grain structure. LPBF-316L typically exhibits columnar and equiaxed grain morphologies. Metal additive manufacturing is a process that depends on the quality of the feedstock powder to determine component density, dimensional accuracy, process and product quality, and reproducibility. Since fine powder particles have a greater surface area, they absorb laser energy more effectively, yielding a denser product. A wide particle size distribution leads to higher densification of the powder bed, because smaller particles are positioned between larger ones.

A potentiodynamic polarization test is conducted in accordance with ASTM F2129 on the developed AM part to assess corrosion behavior. It is necessary to test novel objects in an environment similar to the fluids found in the human body before implanting them into the body [72]. Implant fluids used in *in vitro* corrosion testing include human serum, phosphate buffer saline, Hanks solution, and Ringers solution. As compared to conventional manufacturing methods, AM parts have a refined microstructure and an even distribution of Cr, leading to better corrosion resistance.

Added to this, the continuous heating and cooling cycles involved in the DMLS process can induce residual stresses in AM parts. Residual stress reduces the strength of the part, creates cracks on the outer surface, and distorts it, resulting in a lower quality product. The laser beam causes a high-temperature region to form on a layer. This region tries to expand but is surrounded by low-temperature powder, which limits expansion. Therefore, compression stresses are induced in that region. A layer thickness of less than 28 μm and parts with a more porous structure has been found to have a larger magnitude of residual stresses [73]. Although resid-

ual stresses are inherently present in AM parts, their intensity can be reduced by optimizing laser power, layer thickness, scan speed, and preheating the base plate, or by applying HT and shot peening. Residual stresses are measured by X-ray diffraction, neutron diffraction, or magnetic Raman methods. Additionally, a number of destructive and nondestructive measurement methods are available [74–76].

Tab. 9.3: Relationship between material property and process parameters.

Material property	Desired outcome from process	Process parameter influencing outcome
Porosity [81]	Less porosity for better strength, porous structure expected for some applications	Laser power, VED, scan pattern, morphology
Strength [82]	Higher strength	Laser power, VED, scan pattern, morphology
Wear rate [77]	Higher	Heat treatment and surface coating
Surface roughness [78]	Lower value desired in all cases	laser power, scanning speed, and layer thickness, post-processing
Residual stresses [79]	Lower magnitude desires as higher value leads to dimensional distortion	“laser power, scanning speed, and layer thickness” and building direction
Corrosion resistance [80]	Higher	Heat treatment and surface coating

9.6 Conclusions

AM is revolutionizing manufacturing by producing complex geometry parts with remarkable accuracy. LPBF fusion is the most used variation of AM since it works better with complex geometries with more precision. The purpose of this article is to summarize the DMLS process, its parameters, and defects in the product, post-processing, and application in the biomedical field. From the current study, the following conclusions have been drawn:

1. Porosity in AM parts cannot be eliminated. However, we can reduce its effect on material strength by using optimal process parameters such as powder feed, gas flow, laser power, scan speed, and layer thickness. Also, post-processing like HT gives enhanced mechanical and tribological properties to printed parts.
2. By using HT and mechanical post-processing, such as shot blasting and shot peening, and part defects are reduced, giving better surface properties and microstructure.

3. In AM, porosity, residual stresses, stair-stepping, and balling effects are some of the significant defects. Although these defects cannot be eliminated, their effects can be reduced with suitable processing parameters and post-processing.
4. 3D printing is capable of producing human bone implants, surgical equipment, biomodeling, and specialized drug delivery. It is becoming popular due to its ability to produce customized products in less time and cost.
5. This work helps in relating the different process parameters to mechanical characteristics, remaining or residual stresses, surface irregularities, dimensional exactness, and microstructure development. Further steps and experiments need to be performed to ultimately create a plan between the processes, boundaries, and extreme quality properties of a manufactured part. When properly thermally post-processed, stainless steel and LPBF can produce the highest quality parts compared to other methods.
6. Although many researches have been conducted in this field, there still remain some research gaps related to reduced ductility and elongation properties of materials resulting from thermal post-processing parameters. Also, various researchers have not considered the deformation mechanisms when subjected to different loading conditions.

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10 Finite element method investigation on delamination of 3D printed hybrid composites during the drilling operation

Abstract: Composite materials are mostly employed in structural components but offer several other uses. One of the crucial activities in composite structures is drilling, which is usually the last one performed during assembly. Delamination in the drilling of the composite structure is a significant issue that can result in refusal and cause a substantial loss. Delamination can lead to poor assembly tolerance and long-term performance degradation, in addition to lowering the laminate's structural integrity. The current work focuses on composite material drilling-related delamination. Spindle speed, feed, and interactions will be studied for their impact on drilling's cutting characteristics. From the results, it can be observed that the quality of drilled hole and interlaminar bonding is improving with the increase in spindle speed.

Keywords: Composite material, drilling, delamination, spindle speed, feed rate

10.1 Introduction

Drilling delamination refers to the formation of cracks or separation at the interface between layers or materials in a composite structure during drilling operations. Delamination can occur due to various factors such as high stress concentrations, shear forces, and material inhomogeneity. Understanding and mitigating drilling delamination is crucial as it can significantly impact the structural integrity and performance of composite components. During the drilling process, a rotating drill bit applies

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forces to the composite material, resulting in the removal of material and the generation of heat. Several mechanisms contribute to delamination:

Shear forces: As the drill penetrates the composite material, shear forces are generated in the vicinity of the drill hole. These shear forces can exceed the interlaminar shear strength of the composite, leading to delamination between adjacent layers.

Frictional heating: Friction between the drill and the composite generates heat, which can soften the matrix material and reduce interlaminar strength. Increased temperatures can also degrade the adhesive properties at the interface, making it more susceptible to delamination.

Compressive stresses: Compressive stresses can arise in the material near the drill hole due to the drilling forces. If these stresses exceed the compressive strength of the composite or are not adequately supported by the surrounding material, delamination can occur.

Tool geometry and sharpness: The design and condition of the drill bit can significantly influence delamination. Dull or improperly designed tools can create higher stresses and lead to more severe delamination.

To analyze and mitigate drilling-induced delamination, finite element analysis (FEA) can be used. FEA allows for the simulation of drilling operations and the evaluation of stress distributions, strain levels, and the likelihood of delamination. By optimizing parameters such as cutting speed, feed rate, tool geometry, and drilling techniques, it is possible to minimize the occurrence of delamination. Additionally, material selection, composite layup design, and surface preparation techniques can also play a crucial role in reducing drilling delamination. Choosing suitable matrix materials, reinforcing fibers, and interfacial adhesives with appropriate properties can enhance the interlaminar strength and improve resistance to delamination.

There are several types of delamination that can occur in composites, including:

1. **Interlaminar delamination:** This is the most common type of delamination in composite materials, where separation occurs between adjacent layers within the laminate. Interlaminar delamination can be caused by various factors such as high stress concentrations, shear forces, improper curing, impact loads, or environmental effects.
2. **Intralaminar delamination:** Intralaminar delamination refers to the separation or cracking of individual layers within the composite laminate. This can occur due to manufacturing defects, voids, resin-rich or resin-poor areas, or poor adhesion between layers. Intralaminar delamination can significantly affect the mechanical properties and structural integrity of the composite.
3. **Delamination at interfaces:** Delamination can also occur at interfaces between different materials in a composite structure. This includes delamination between layers of different fiber orientations, between composite plies and adhesive layers, or between the composite and a substrate material. Poor bonding, weak interfacial

properties, or differential thermal expansion between materials can lead to delamination at these interfaces.

4. **Delamination at free edges or holes:** Delamination can occur at free edges or around holes or cut-outs in composite structures. Stress concentrations, shear forces, or inadequate reinforcement in these regions can contribute to delamination.
5. **Impact-induced delamination:** High-velocity impact can cause delamination in composites. The impact energy can initiate and propagate cracks between layers, resulting in significant damage. Impact-induced delamination is a critical concern in applications where composite structures are subjected to dynamic loads or potential impact events.

10.1.1 Peel-up delamination

Peel-up delamination is a specific type of failure observed in 3D printed parts, particularly those produced using fused deposition modeling technology. It is characterized by the separation or lifting of individual layers within the printed object, usually occurring at the edges or corners.

The primary cause of peel-up delamination is insufficient adhesion between the layers of the printed part. This lack of adhesion can stem from various factors, including inadequate layer bonding, incorrect layer height settings, or excessive extrusion of the printing material. Additionally, environmental conditions such as high temperature or humidity can contribute to this type of delamination. Figure 10.1 represents schematic diagram for Peel-up Delamination.

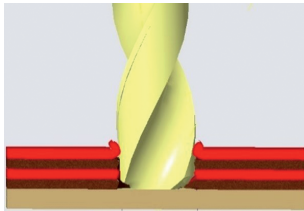


Fig. 10.1: Peel-up delamination.

Preventing peel-up delamination requires several considerations. It is crucial to ensure proper bed adhesion, which involves optimizing the adhesion between the printed part and the build platform. Adjusting the layer height and extrusion parameters to their appropriate values is also essential to promote strong layer adhesion. Controlling the environmental conditions, such as temperature and humidity, during the printing process can help mitigate the risk of delamination. It's worth noting that peel-up delamination can also result from external mechanical forces exerted on the printed part. In such cases, it is advisable to review and modify the design of the part to minimize or eliminate these forces, thereby reducing the likelihood of delamination.

10.1.2 Pull-out delamination

Pull-out delamination, also known as “interlaminar delamination” or “cohesive delamination,” is another type of failure that can occur in 3D printed parts. It is characterized by the separation of layers within the printed object, typically in the middle or at the center of the part. Unlike peel-up delamination, which arises from a lack of adhesion between layers, pull-out delamination occurs due to insufficient cohesion between the layers. Figure 10.2 represents a schematic diagram for pull-out delamination.

Several factors can contribute to pull-out delamination:

1. **Incorrect temperature setting:** Inadequate temperature control, either too high or too low, can lead to a lack of cohesion between the layers, reducing their bond strength.
2. **Over-extrusion:** Extruding the material at a rate that is too high can hinder the effective bonding between layers, resulting in reduced cohesion.
3. **Incorrect layer height:** Setting the layer height too thin can compromise the bonding strength between the layers, making them more susceptible to delamination.
4. **Incorrect cooling:** Inadequate cooling during the printing process can negatively impact the cohesive properties between the layers, leading to increased chances of delamination.

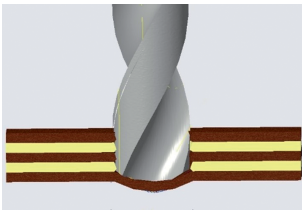


Fig. 10.2: Pull-out delamination.

To prevent pull-out delamination, several precautions should be taken:

- Ensure correct temperature settings, maintaining an optimal temperature range for the specific material being used to promote strong cohesion between layers.
- Set an appropriate layer height, considering the material properties and printer capabilities, to achieve adequate bonding strength between the layers.
- Control the extrusion rate to avoid over-extrusion, allowing for optimal material deposition and promoting better layer cohesion.
- Implement proper cooling mechanisms during the printing process to facilitate efficient bonding and enhance the cohesive properties of the printed part.

Additionally, using materials known for their good cohesive properties, such as ONYX, can contribute to reducing the risk of pull-out delamination.

It is important to note that mechanical forces applied to the printed part can also induce pull-out delamination. In such cases, it is advisable to review the part design to minimize or eliminate the effects of these forces, ensuring structural integrity and reducing the likelihood of delamination. By considering these preventive measures and optimizing the printing parameters, the occurrence of pull-out delamination can be minimized, resulting in improved quality and reliability of 3D printed parts.

A study focuses on the modeling and failure analysis of 3D printed woven composite plates with a hole under both tensile and shear loading conditions [1]. The analysis involves utilizing finite element (FE) software to construct woven cells using stacking sequences. These woven cells are then interconnected to establish the FE model of the woven laminate. By employing this approach, the researchers are able to investigate the behavior of the 3D printed woven composite plates and analyze their failure characteristics.

FE models are presented to demonstrate the effectiveness of transitions in increasing translaminal fracture toughness [2]. The study involved designing specific microstructures that were subsequently 3D printed using continuous glass and carbon fibers. The specimens predominantly consisted of glass fibers, but incorporated localized carbon fiber strips. To ensure accurate failure analysis, a novel compact tension specimen with a side groove was developed. The findings revealed significant improvements in toughness, ranging from 20% to 60%, after the crack propagated through the carbon fiber strips. These results highlight the potential of utilizing localized reinforcement as a powerful strategy to enhance toughness in critical areas where it is most needed.

Investigation on carbon fiber-reinforced polymer (CFRP) composite plate with a thickness of 4 mm was manufactured to examine its drilling behavior [3]. The drilling behavior was investigated experimentally under various drilling parameters. Specifically, the impact of different drilling parameters, including axial feed rates (45, 63, and 90 mm/min), spindle rotational speeds (250, 710, and 2,000 RPM), and three different drill bit geometries, was analyzed. The study focused on two machining characteristics: torque and radial force, as well as the highest temperature reached during the drilling process of the CFRP composite. To optimize the drilling parameters, the Taguchi technique was employed. Additionally, the relative significance of the drilling parameters was determined through the analysis of variance (ANOVA). This allowed for a comprehensive evaluation of the effects of each parameter on the drilling performance of CFRP composites.

The development and implementation of the delamination plug-in was introduced in this investigation and reported that an open-source tool designed for modeling delamination tests within the ABAQUS software [4–6]. The specialized plug-in discussed here is specifically designed to cater to the stochastic modeling needs of 3D printed composites. It is developed to address the unique challenges and characteristics associated with modeling and simulating these types of composites.

A recent investigation by Dang et al. [7] and Cao et al. [8] examined three configurations of the double cantilever beam (DCB): carbon/carbon, Kevlar/Kevlar, and carbon/Kevlar hybrid interfaces. The findings of the investigation indicate that the interlaminar failure of carbon fiber is significantly influenced by void defects that arise during the 3D printing process. Conversely, it was observed that Kevlar fiber significantly enhances the interlaminar fracture toughness due to improved bonding between layers and the presence of denser bridging fibers. Additionally, the study proposes an innovative concept for the hybrid interface based on the characterization analysis of carbon–Kevlar composites. This concept introduces a novel approach that combines the unique properties of carbon and Kevlar fibers in order to optimize the interlaminar interface and enhance the overall performance of the composites. This idea presents an innovative approach to optimize the interlaminar properties by combining the advantages of both carbon and Kevlar fibers. By investigating the interlaminar fracture behavior and comparing different fiber-reinforced configurations, this study provides valuable insights into enhancing the interlaminar fracture toughness of 3D printed continuous fiber-reinforced composites.

Many researchers [9–12] performed investigation on double cantilever beam test at various displacement rates, namely 1, 10, 100, and 500 mm/min. The results demonstrate that the mode I fracture toughness remains consistent across the entire range of displacement rates studied. Scanning electron micrographs reveal distinct delamination patterns at different displacement rates. At 1 mm/min, interfacial debonding dominates, while a river pattern is observed at 500 mm/min. Interestingly, no bridging effect is observed at any of the displacement rates. Furthermore, the experimental and numerical results obtained from the force-displacement curves show a strong agreement, with a maximum difference of only 14%. This indicates that the numerical simulations performed using the Delamination Plug-in accurately capture the mechanical behavior of the delamination process as observed in the experimental testing. Additionally, the crack growth observed in both the experimental and numerical analyses exhibit a high level of comparability, with a variation of less than 15%. This suggests that the delamination plug-in successfully captures the progression and propagation of cracks during the delamination process [13, 14].

10.2 Finite element modeling

The PTC Creo software designed the 50*50*5 mm³ part of sandwiched laminates with the twist drill at the center. The developed part with the stp format is then imported into the ANSYS Workbench Software. Then the explicit dynamic analysis model is selected, and the imported part is assigned with the Onyx and Fiberglass material layers in a sandwich manner. Figure 10.3 shows PTC Creo assembled Sandwich laminates with Twist Drill Bit.

The boundary conditions, such as fixed support, are assigned to the sandwich laminate at the corners. The twist drill is rotated clockwise with the Remote displacement command

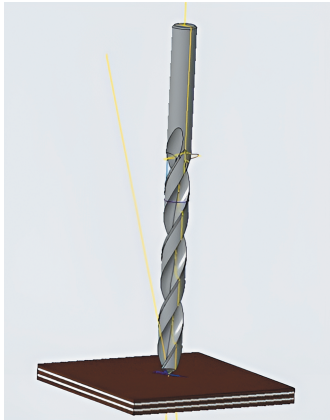


Fig. 10.3: PTC Creo assembled Sandwich laminates with Twist Drill Bit.

by providing the boundary conditions $U_x = U_y = 0$. The tool travel distance of 20 mm is provided in the Z direction. The rotational moment is provided in the Z direction with the required RPM. Figure 10.4 represents (a) Fixed support (b) Remote Displacement during FEA.

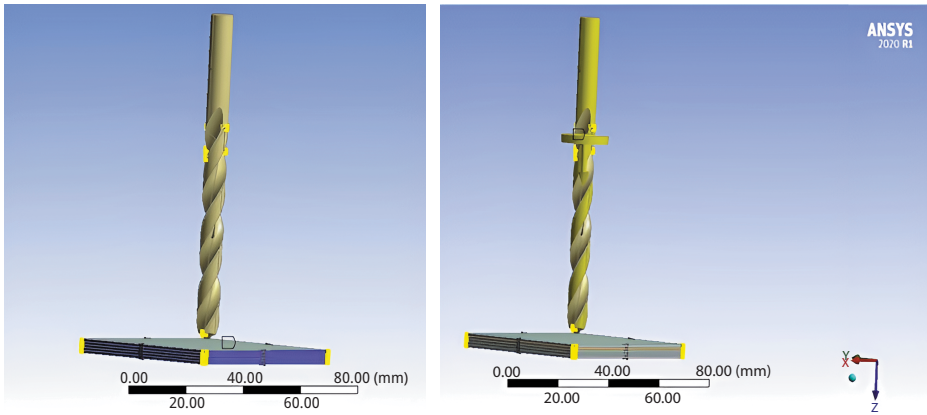


Fig. 10.4: (a) Fixed support (b) Remote Displacement.

10.3 Results and discussion

10.3.1 Finite element damage models

Equivalent Von-Mises stress: The Equivalent Von-Mises Stress is calculated through the Ansys Workbench Software, and it is observed that the stress values are increas-

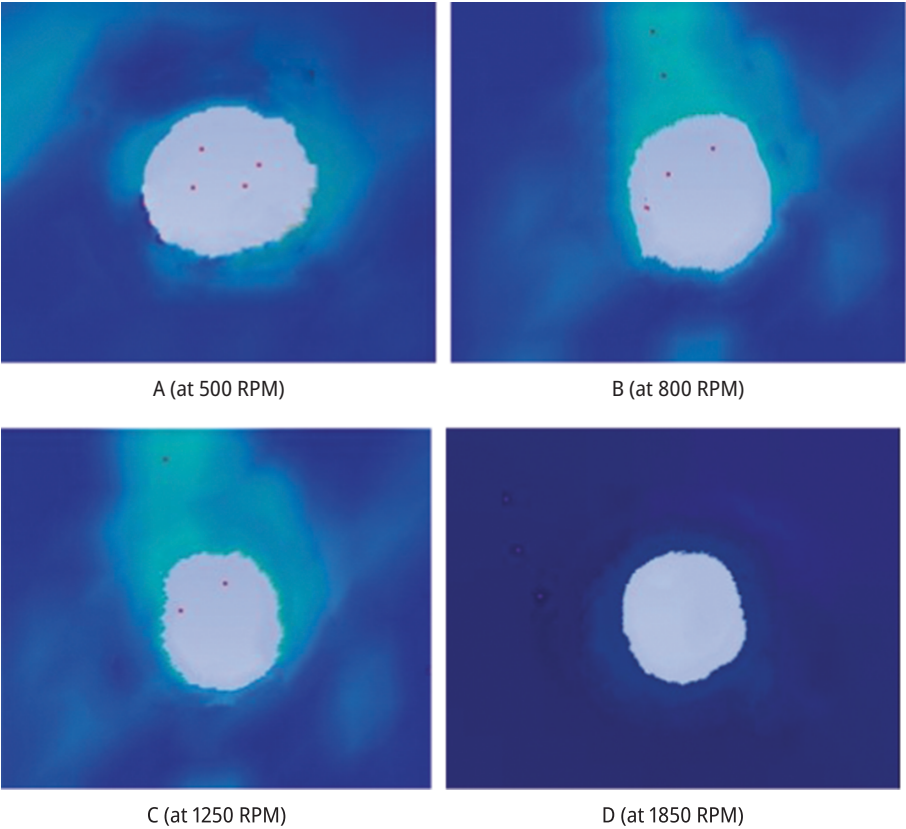


Fig. 10.5: Images of FEA drilled holes on different samples.

ing with the increase in Spindle Speed (RPM). Figure 10.5 shows Images of FEA drilled holes on different samples drilled with different speeds. Whereas, Fig. 10.6 shows Equivalent Von-Mises Stress developed during the delamination of hole drilling process. Table 10.1 shows the Equivalent Von-Mises Stress of the drilled holes at different RPM.

Tab. 10.1: Equivalent Von-Mises Stress.

Sl. No.	Spindle Speed (RPM)	Equivalent Von Mises Stress (MPa)
1	500	307
2	800	377
3	1250	397
4	1850	1134

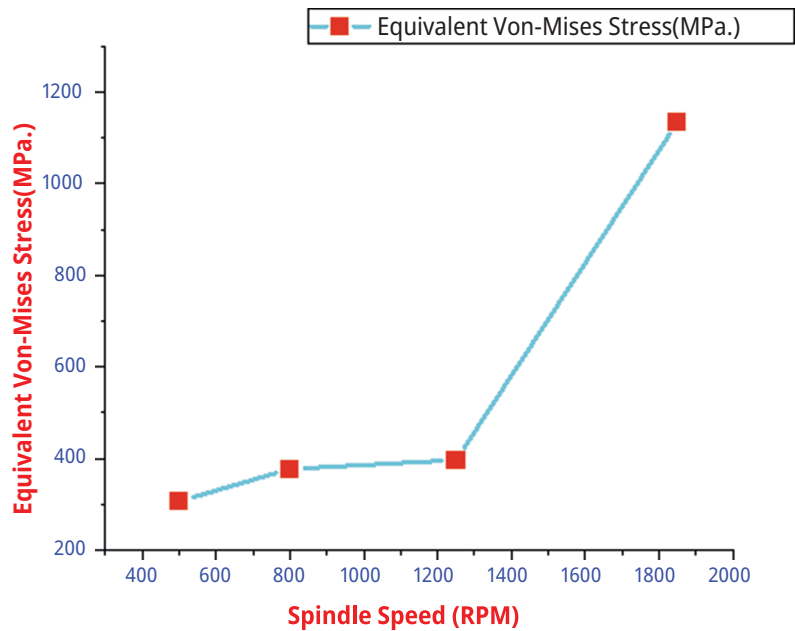


Fig. 10.6: Equivalent Von-Mises Stress.

10.3.2 Determination of delamination factor after simulation

Delamination can be defined as the ratio of the maximum diameter of the drilled hole to the diameter of the drilled hole. The Delamination factor can be calculated by the formula as defined below:

The factor of delamination (F_d) = maximum diameter of the drilled hole/actual diameter of the drilled hole. The maximum diameter of the drilled hole is obtained by the image processing software, i.e., ImageJ. Table 10.2 shows detailed results obtained during FEA and their corresponding delamination factor readings.

Tab. 10.2: FEA Delamination factor Readings.

Spindle Speed (RPM)	Maximum Diameter (mm)	The Factor of Delamination (F_d)
500	9.3	1.17
800	8.4	1.05
1250	7.9	0.98
1850	7.7	0.96

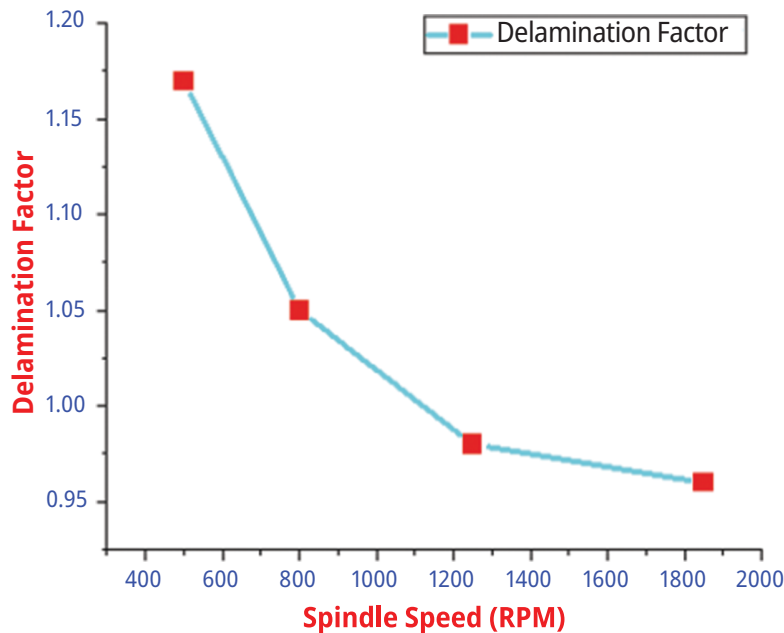


Fig. 10.7: FEA Delamination factor.

From Fig. 10.7, it can be observed that the delamination factor decreases with the surge in the spindle speed (RPM), favoring the fine quality of the drilled hole. It can be said that as the spindle speed increases, it reduces the delamination, so to obtain the fine quality and precise measurement of the spot, high-speed drilling is recommended.

10.4 Conclusion

This study presents both experimental and finite element analysis (FEA) investigations into the delamination phenomenon in 3D printed composite laminates. Based on the findings, the following conclusions can be drawn:

1. The primary cause of entry delamination is the removal of unfinished fiber from the upper sheet by the inferior cutting edge of the drill bit. This fiber is pulled off the surface through the helical groove of the drill bit.
2. Exit delamination occurs due to a reduction in material sustenance thickness and weakened bonding between layers as the drilling depth increases.
3. Increasing the spindle speed has a positive effect on reducing the delamination rate. Higher speeds result in more effective material cutting, while lower speeds lead to poor material removal rates, thereby increasing the likelihood of delamination.

4. The tensile strength of the composite laminate improves when it contains fewer fiberglass layers. The addition of fiberglass layers enhances the stiffness of the Onyx material but reduces its tensile strength.

10.5 Scope of future work

This study aims to provide an understanding of the causes of delamination in composite sandwich laminates. However, it recognizes that future research should focus on modifying the configuration of the laminate to mitigate delamination. One specific area that requires investigation is the interaction between the drill bit and the laminate when a thermal-mechanical connection is present. It is essential to explore the heat transfer mechanism and the dynamic temperature field that occurs during the drilling process. Additionally, it is crucial to develop a damage model that accounts for the thermal-mechanical link in order to accurately predict and assess the occurrence of delamination. By investigating the thermal-mechanical interaction between the drill bit and the laminate, this research aims to provide insights into the underlying mechanisms that contribute to delamination. The findings from this study will be valuable for improving drilling processes and developing effective strategies to prevent or minimize delamination in composite sandwich laminates.

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11 Analyzing the dimensional stability in direct ink written composite ink: a machine learning approach

Abstract: Direct ink writing (DIW) is a burgeoning additive manufacturing (AM) technique esteemed for its cost-effectiveness. The meticulous control of process parameters, encompassing printing speed (V), the distance between the printing bed and nozzle bottom (h), pulses per microliter for material extrusion (p), and extrusion multiplier (m), holds paramount significance in ensuring precise dimensional accuracy in DIW-produced models. Insights about the extent of impact of these four parameters are significant to maintain dimensional accuracy. In this work, k -means clustering, an unsupervised machine learning algorithm from the Scikit-learn machine learning library of Python has been applied to identify clusters in an experimental dataset that predicts the dimensional accuracy of printed PDMS-CNT ink. In this research, experimental data of the four-dimensional input matrix is taken to estimate the impact of the individual process parameters on the cross-sectional deviation. The elbow method and silhouette coefficient were used to find out the optimum number of clusters for higher distinguishability. The high distinguishability ensured that the future experimental runs can be used to predict the appropriate cluster and thus the dimensional accuracy of printed PDMS-CNT ink.

Keywords: 3D printing, direct ink writing, machine learning, composite inks, k -means clustering, Python

11.1 Introduction

Additive manufacturing (AM), alternatively known as 3D printing (3DP), is a nascent and auspicious domain that has captivated considerable attention from diverse industries [1]. Direct ink writing (DIW), an intricate technique of 3DP, involves the successive expulsion of an ink stratum through a fine submicron nozzle. This method allows for the facile deposition of gels, pastes, colloids, and polymers, exhibiting both eco-

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nomical and versatile attributes. Notably, DIW excels in its capability to function at ambient temperatures, thereby enabling the fabrication of materials devoid of direct liquefaction or sintering. Furthermore, it is imperative to acknowledge that DIW imparts a remarkable degree of flexibility concerning the scale and patterning methodologies [2].

Achieving proficiency in DIW requires printable ink and optimized process parameters. Ink rheology, including shear-thinning behavior and high storage modulus, influences extrusion, shrinkage, and shape retention. DIW process parameters related to equipment setup significantly impact dimensional accuracy [3].

In the realm of 3DP, ensuring the dimensional accuracy of deposited layers is crucial to achieve high-quality end products. Presently, extensive research is being conducted in the field of AM quality control, with a focus on the regulation and surveillance of 3D printed layers. Significant strides have been made in predicting the in-plane shape of printed layers, resulting in enhanced geometric precision for products fabricated using fused deposition modeling (FDM) techniques. Furthermore, a comprehensive framework for monitoring the quality of 3DP has been proposed, employing layer-by-layer inspection methods. To optimize the continuity and uniformity of extruded filaments in DIW, screening experiments have been employed to identify the optimal printability windows for each process parameter, ensuring optimal performance [4]. In recent times, numerous studies have focused on the selection of process parameters in DIW techniques. However, these studies have fallen short in determining the optimal values for these parameters, and only a limited number of studies have explored the impact of process parameter in DIW by establishing a fine relation between them. Therefore, it becomes crucial to delve into the significance of each process parameter and identify the ideal configuration for each parameter to enhance the dimensional accuracy of DIW-produced parts.

The exploration of machine learning (ML) algorithms is underway as a potential solution to enhance control and automation in the complex extrusion-based printing process. Various endeavors have been made to employ ML models for specific techniques and applications, aiming to optimize the AM processes [5]. In FDM, a convolutional neural network deep learning model was used to swiftly detect and mitigate any malicious flaws, enabling real-time identification while reducing the need for extensive human intervention in the quality control process [6]. An iterative optimization technique Bayesian optimization has been employed to enhance the performance of different parameters in DIW 3DP, including the composition of biomaterial inks, bed temperature, reservoir temperature, printing speed, and extrusion pressure [7]. A neural network algorithm has been implemented to enhance the precision of dimensional measurements in 3D printed parts produced through powder bed fusion [8]. *k*-Means clustering remains uncharted territory in the realm of optimizing 3DP techniques. It is essentially an unsupervised ML technique where clustering methods are commonly employed.

This study focused on identifying the DIW process parameters using 3DP analyses. To estimate the dimensional accuracy of printed polydimethylsiloxane (PDMS)–multi-

walled carbon nanotube (MWCNT) ink, a k -means clustering algorithm was proposed to determine the relative importance of each parameter. Two complimentary techniques, elbow point method and silhouette coefficient method, were used to obtain the optimum number of clusters for high level of distinguishability. Rheological studies were also included to assess the extrudability and shape retention of the formulated PDMS-CNT ink.

11.2 Materials and methodology

PDMS polymer matrix, specifically Sylgard-184 Silicone Elastomer, was enhanced with MWCNTs. MWCNTs with an outer diameter of 50 nm and a length of 10–30 μm were obtained from Sisco-Research Laboratories Pvt. Ltd., India. The curing agent and Sylgard-184 were sourced from Dow Europe GmbH, Switzerland. Isopropyl alcohol (IPA) was obtained from Sigma-Aldrich, USA. Polymeric composite inks were prepared by combining silicone elastomer with varying volume percentages (vol%) (10, 20, 30, 40, and 50) of MWCNT. To prepare PDMS-CNT inks, MWCNTs were initially dispersed in IPA at a weight ratio of 1:40. The dispersion was sonicated for 30 min, followed by the addition of silicone elastomer base and stirring for another 30 min. The prepared mixture was then stirred at 800 rpm on a magnetic stirrer at 80 $^{\circ}\text{C}$ for complete IPA evaporation. The curing agent was subsequently added and stirred before being filled into the syringe.

To evaluate the rheological properties of the composite inks, amplitude sweep (strain), frequency sweep, and stress-ramp tests were carried out. The formulated samples were subjected to a strain sweep ranging from 0.01% to 100% at a frequency of 1 Hz. Additionally, frequency sweeps from 0.1 to 10 Hz were performed on all ink samples at a strain of 10% within the linear viscoelastic region [9].

In order to identify significant process parameters for the DIW-based 3D printer (Hyrel3D, USA), trial runs were conducted by varying the printer's parameters and depositing filaments. The inner diameters of the nozzle (D_n) and syringe (D_s) were found to be equipment-dependent parameters. Parameters such as printing speed (V), gap between the printing bed and nozzle bottom (h), pulses per microliter for material extrusion (p), and extrusion multiplier (m) were determined to have a significant impact on print quality. To generate a printing window, the ratio of D_n and h (R_e), V , and the product of p and m (R_f) were selected as parameters for a comprehensive study using full-factorial experimentation with 27 experiments at three levels (Tab. 11.1).

A circular ring with a diameter of 30 mm and a thickness of 0.70 mm was chosen for printing using the DIW-based 3D printer equipped with a 0.61 mm nozzle (Fig. 11.1 (a)). The deviations between the computer-aided design (CAD) model and the physical part were measured using a profilometer (Zygo-NewView 9000) (see Fig. 11.1(b)). The deposited circular ring was divided into four circular arcs, with the first arc excluded

to ensure consistent measurements. This exclusion was made due to the observation that the flow percentage was not maintained at its full potential. A total of 153 measurements were taken at three different arc lengths (L) to determine the width and height of the printed samples:

$$M_{ij} = \begin{bmatrix} a_{j01} & a_{j02} & a_{j03} & \dots & a_{j17} \\ a_{j18} & a_{j19} & a_{j20} & \dots & a_{j34} \\ a_{j35} & a_{j36} & a_{j37} & \dots & a_{j51} \end{bmatrix} \quad (11.1)$$

In this matrix, i is the sample number varies from 1 to 27 and j ($=1, 2, 3$) is the arc number. M_{ij} represents the number of measurements done in a particular arc of each sample.

Tab. 11.1: Levels of process parameters.

Parameter	Range	Level 1	Level 2	Level 3
h	0.05–0.15 mm	0.05	0.10	0.15
R_f	6–12	6	9	12
V	(4–8) mm/s	4	6	8

The experimental dataset with measurements of printed layers possessing primitive geometry was created for developing the unsupervised predictive models. Since there are no predetermined labels applicable to the output parameter aka cross-sectional deviation, hence unsupervised algorithms such as clustering is suitable for this study. k -means clustering, an ML-based algorithm, was used in this study for the clustering of the experimental data. The clusters were used to gauge the impact of the process parameters on cross-sectional deviation. The python language was used in building the k -means clustering model.

11.3 Results and discussions

11.3.1 Rheological characterization

Rheology assumes the most pivotal role in 3DP via the DIW technique; thus, rheological characterization has been conducted for all the formulated inks. The shear stress ramp test revealed a yield stress value of 155.45 Pa for the C50 ink (Fig. 11.1(c)), denoting that the ink remains at rest until the shear stress surpasses this threshold. All the inks (C00, C10, C20, C30, and C40), except for C50, exhibited a consistent viscosity trend across a wide range of shear rates, rendering them nonprintable due to their limited shear-thinning behavior. Conversely, the C50 ink displayed a notable shear-

thinning trend, confirming its pseudoplastic behavior, which makes it suitable for extrusion (Fig. 11.1(d)) [2]. The ink exhibited significant shear-thinning characteristics as the viscosity decreased with increasing shear rate. Notably, the C00 ink demonstrated a substantial disparity between the storage modulus (G') and the loss modulus (G''), indicating its poor shape retention capacity. However, the C50 ink showcased an impressive solid-like response, with G' surpassing G'' , signifying minimal shrinkage and excellent shape fidelity (Fig. 11.1(e)). In summary, rheological characterization confirmed the superior printability of the C50 ink. Following ink formulation, the subsequent focus of this study lies in identifying and optimizing the parameters associated with the DIW process.

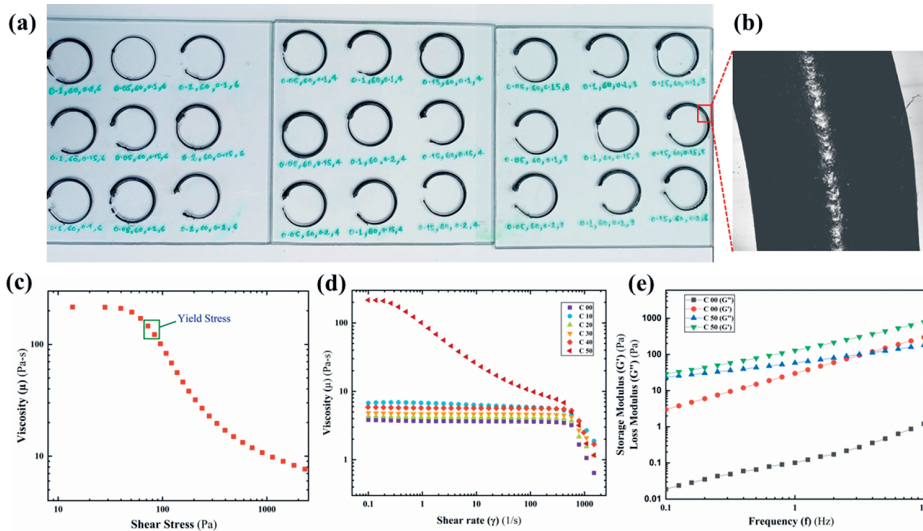


Fig. 11.1: (a) Printed samples; (b) a magnified examination of the printed sample during profilometer measurements; (c) evaluation of the yield stress value for C50 ink; (d) viscosity versus shear rate plot; (e) G'' and G' versus frequency plots for C00 and C50 inks.

11.3.2 3DP, measurements, and prediction results

3DP of circular rings was carried out after filling the syringe with formulated PDMS-CNT composite ink, as per the different full-factorial combinations of parameters. A total of 51 observations were recorded by measuring heights and widths at each arc length. The cross-sectional area deviation of the printed sample has been taken for the development of ML model. The python code has been developed to build clusters for each input parameter. The clustering technique is used to partition data into

groups which are called clusters. These are defined as groups of data points that are more like other points in their cluster than they are to data points of other clusters. Clustering helps identify meaningful segments in the data. In this research, the clustering results segment the experimental data into groups with similar cross-sectional deviation, based on the variations of an input parameter. Since there are no predetermined labels attached to the output parameter aka cross-sectional area deviation, hence this problem does not require attaching specific preference for the *false negative* over *false positive* and vice versa [10]. But this makes the performance evaluation on an unsupervised learning model trickier. The evaluation of a clustering model is based on the comparison of the intracluster distance and the intercluster distance, to decide how well the clusters are separated. Hence, the number of clusters is critical in any clustering algorithm. Two methods, (i) elbow point and (ii) silhouette coefficient method, are predominantly used to decide the number of clusters [11].

In the elbow method, multiple k -means models are built, increasing k with each iteration and the sum of square error (SSE) is computed for each iteration. In the plot of SSE versus number of clusters, SSE continues to decrease number of clusters increase. As more clusters are added, the distance from each point to its closest cluster's centroid will decrease. There is a point where the SSE curve starts to bend known as the elbow point. The x-value at this point is a reasonable trade-off between SSE and number of clusters [12]. In the silhouette coefficient method, the intracluster distance is estimated as

$$a(i) = \frac{1}{|C_I| - 1} \sum_{j \in C_I, i \neq j} d(i, j) \quad (11.2)$$

where $|C_I|$ is the number of points belonging to cluster C , and $d(i, j)$ is the distance between data points i and j in the cluster C_I . Small score $a(i)$ indicates a good clustering because it is close to the points within the same cluster. In a similar manner, the intercluster distance is expressed as

$$b(i) = \min_{j \neq I} \frac{1}{|C_J|} \sum_{j \in C_J} d(i, j) \quad (11.3)$$

Once the intra- and intercluster mean distances are obtained, the Silhouette score is defined as

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}} \text{ for } |C_I| > 0 \text{ and } s(i) = 0 \text{ for } |C_I| = 0 \quad (11.4)$$

In the python code developed for this research, the elbow points are obtained by using the *KneeLocator* method of the *kneed* module. The *silhouette_score* method of the *sklearn.metrics* has been used to compute the silhouette coefficients.

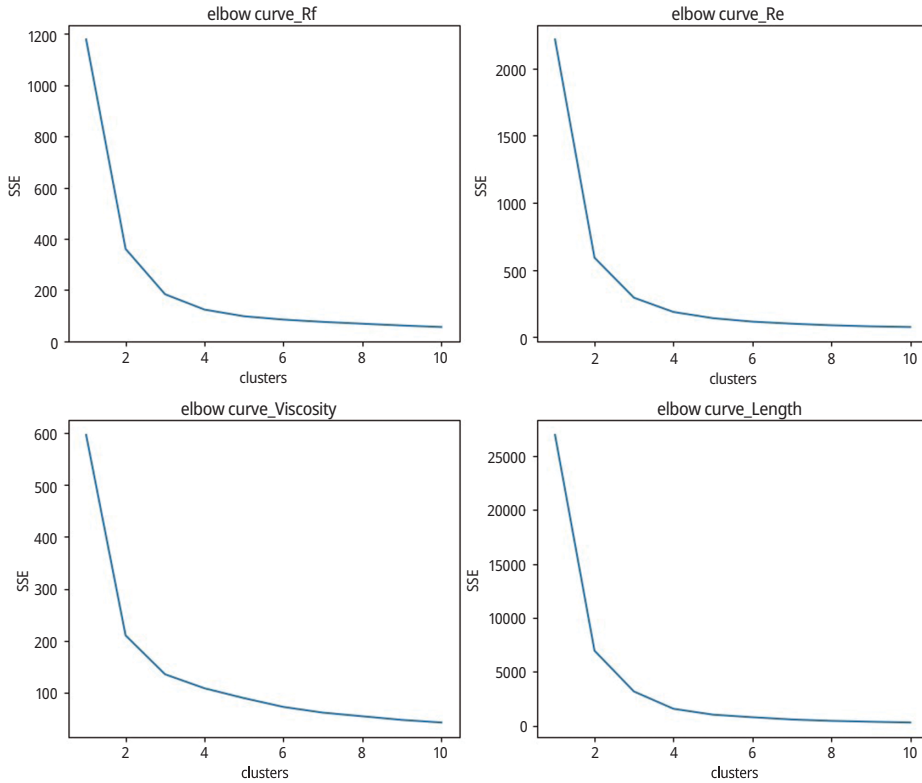


Fig. 11.2: Elbow curves for the input parameters: R_f , R_e , viscosity, and length.

It is not always straightforward to determine the elbow point from the elbow curve. In this case also x -values 3 and 4 are very close for all the parameters as shown in Fig. 11.2, hence the *KneeLocator* method is used, which suggests three as the optimum number of clusters for all four parameters. Still there are times when the results of elbow method could be misleading [13]. This is addressed by plotting the silhouette score for multiple clusters. A high silhouette score implies more separated clusters and high distinguishability [14]. The plot of silhouette coefficient scores (Fig. 11.3) for multiple clusters suggests that the optimum number of clusters is three for R_f , R_e , and viscosity (μ) but length (L) parameter has four optimum clusters.

Going by the optimum number of clusters as suggested by the elbow method and silhouette coefficient technique k -mean clustering model was applied to evaluate the extent of impact of these four parameters on the cross-sectional deviation. The model output is shown in Fig. 11.4. The “red,” “green,” and “blue” dots represent the data points belonging to three different cluster labels for R_e , R_f , and μ . Length (L) has an additional cluster depicted by “yellow” dots. The obtained clusters are visibly distinct with almost zero overlap of the data points. R_e value less than 6 shows high dimen-

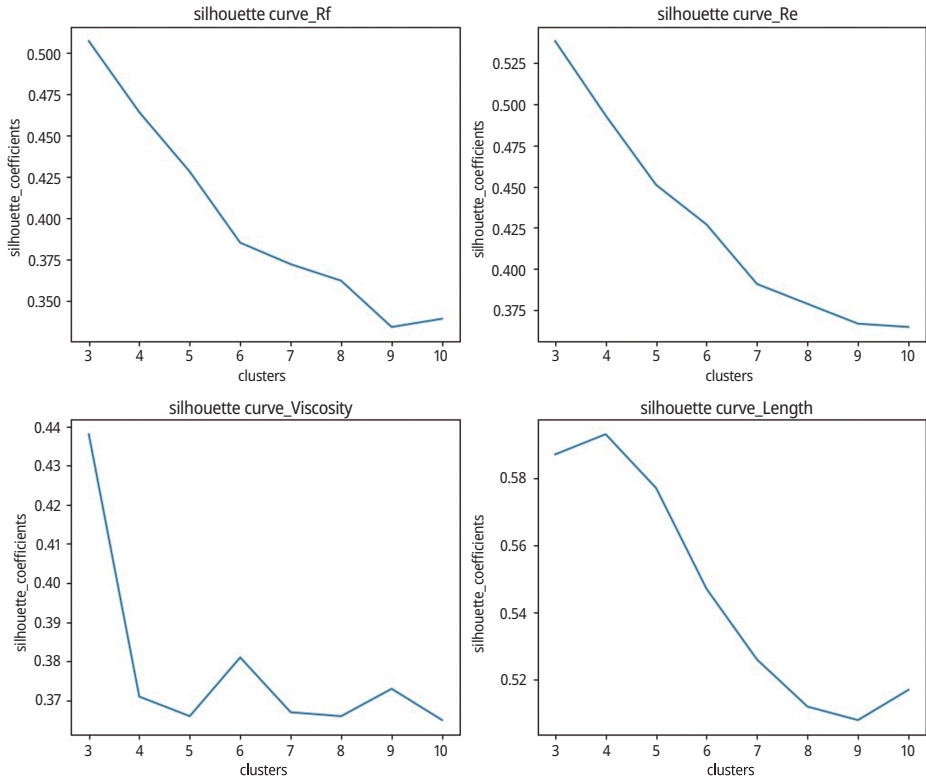


Fig. 11.3: Silhouette coefficient scores for the input parameters: R_f , R_e , viscosity (μ), and length (L).

sional stability, but if it increases beyond 10 there is high risk to the dimensional stability. Similarly, for R_f values more than 10 ensures high stability and viscosity of more than 6.5 is good for dimensional accuracy. The length parameters indicate that there is high risk to the dimensional stability if the length of the beam is increased beyond 37 mm.

11.4 Conclusions

In this present investigation, an extensive examination was conducted to ascertain the influence of diverse printing parameters, comprising V , h , p , and m , on the dimensional precision of 3D printed parts. Rheological examinations of the newly formulated PDMS-CNT inks furnished intricate insights into their extrudability and shape retention characteristics. Based on measured dataset, ML-based k -means clustering model was developed correlating the examined printing parameters on the dimen-

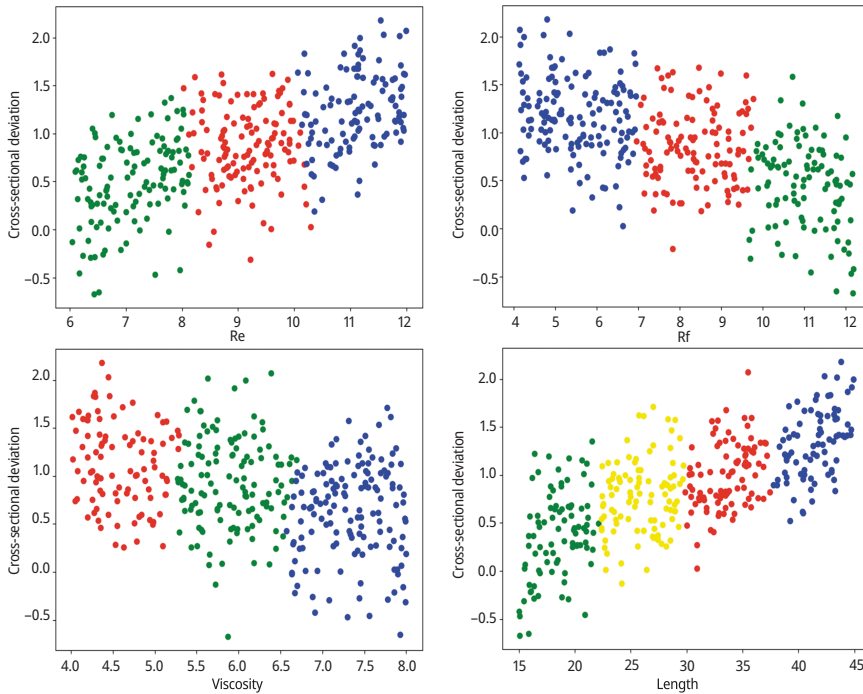


Fig. 11.4: Clusters of cross-sectional area deviation for the input parameters: R_e , R_f , viscosity (μ), and length (L).

sional accuracy of the printed samples. Optimum clusters were decided based on the complimentary techniques, elbow method and silhouette coefficient scores.

The model could be highly useful for printing similar kinds of inks; thus, wastage of materials and time on various trials could easily be avoided. The computational infrastructure and hardware impose limitations while attempting the various ML algorithms. To improve this work further, future research can attempt supervised algorithms such as ANN with more iterations. With advanced computational power, other algorithms such as *support vector machine* and *random forest* can also be attempted.

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12 Recent applications of rapid prototyping with 3D printing: a review

Abstract: In the not-too-distant future, three-dimensional (3D) printing technology is destined to alter our way of life, work, and play in almost every major industry. In today's world, 3D printing is used extensively in numerous industries, including the food industry, construction, and health care. Rapid prototyping technology, also known as 3D printing, helps to create a physical object from a geometrical representation by successively adding materials. It has become an alternative to 2D printing that does not require toners and ink and has reduced the cost of manufacturing in industries. 3D printing has also created a new image in the minds of people and is used in producing things from fashion wear to architecture. 3D printing technology also plays an important role in the medical field by printing functional tissues. It is quite useful in manufacturing as well. As per researchers, the global 3D printing market is expected to expand at a compound annual growth rate of 23.3% from 2023 to 2030. In this chapter, the field of 3D printing technology is explored along with its applications with specific reference to the manufacturing, industrial education, food industry, and medical field. By exploring the applications of 3D printing in manufacturing, education, healthcare, and the food industry, this study aims to provide insights into the benefits, advancements, and transformative capabilities of 3D printing, guiding future research and innovation in this field.

Keywords: 3D printing, fashion, CAD, industry, bioprinting

12.1 Introduction

As the world keeps evolving, new technologies are introduced. In the last few decades, technology is rapidly evolving. Industry 4.0 has resulted in breakthroughs in a variety of fields [1]. Three-dimensional (3D) printing technology, one of Industry 4.0's components, has enabled positive advancements in manufacturing. The process of 3D print-

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ing begins with CAD modeling and ends with a finished product. The term 3D printing covers various processes and technologies making use of software for slicing the three-dimensional model into layers. The layer-by-layer production results in much greater flexibility and a reduction in the cost of manufacturing.

In the early 1980s, the initial technology for 3D printing was developed in response to the technical requirements for rapid design prototypes. Since 2010, it has been widely used and evolved into “**rapid prototyping**” and “**additive manufacturing**” (AM) [2–4]. This widespread use can be demonstrated by the rise of personal printers and the development of 3D printers in various designs and sizes. AM is the name given to the manufacturing technique utilized by 3D printers. Although there are numerous raw materials that can be printed, thermoplastic filaments, photopolymer resins, and powder-based materials are frequently utilized by 3D printing technologies. The use of 3D printers is necessary for the creation of 3D models. The extension “.stl” (standard triangle language) is applied to drawings created in a computer environment using a CAD (computer-aided design) program like AutoCAD, Solid Works, or 3DsMax, as well as to 3D-scanned objects. The file with the “.stl” extension is printed by the 3D printer. Different types of material used for 3D printing are described in Fig. 12.1 [5, 6].

Sr No.	Material	Features
1	ABS(Acrtlontrile butadiene styrene)	1. Tough and Durable 2. Heat and impact resistance 3. Requires a heated bed to print
2	PLA(polylactic acid)	1. Rigid, Strong but Brittle 2. Less heat to resistance 3. Biodegradable
3	PETG(polyethylene terephthalate glycol)	1. Can be food safe 2. Humidity and chemical resistance 3. High Transparency
4	Nylon	1. Strong and Durable 2. Tough and partially flexible 3. Very complex to print on FDM
5	TPU(thermoplastic polyurethane)	1. Flexible and stretchable 2. impact resistance 3. Excellent vibration dampening

Fig. 12.1: Different materials used in 3D printing.

On the basis of material, 3D printers are classified into different categories as depicted in Fig. 12.2.

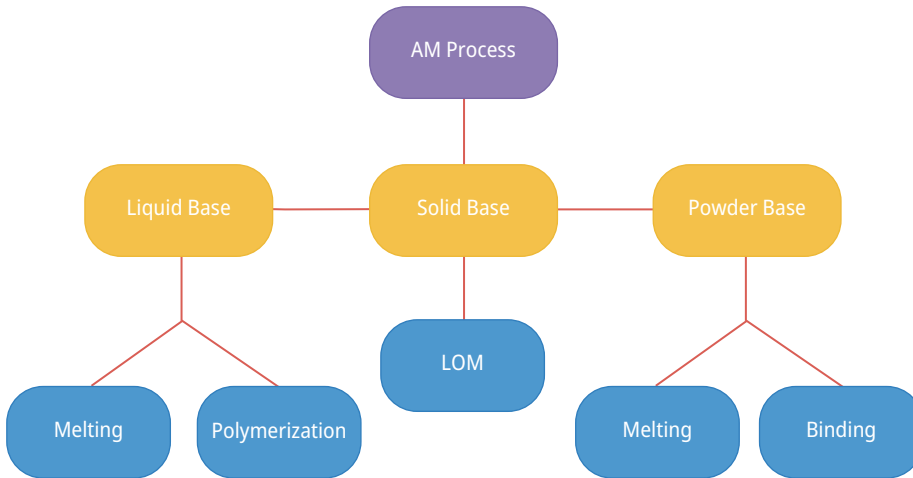


Fig. 12.2: Classification of 3D printers based on materials.

These classifications include:

1. **Liquid base 3D printers:** A liquid resin is a material that is used in liquid base 3D printers, which are also known as stereolithography (SLA) printers. The liquid resin is selectively cured into solid layers through the use of a light source, like a UV laser.
2. **Solid base 3D printers:** Solid base 3D printers are 3D printing machines that have a strong and stable base so they can make accurate and good-looking prints.
3. **Powder base 3D printing:** A type of AM technology known as powder-based 3D printers makes use of a powdered material as the base material for printing objects. To fuse the powdered material and produce a solid, 3D object, the printer applies a liquid binder to the powdered material in a layer-by-layer manner with a precise inkjet head.

The preceding section provides an overview of the evolution, processes, materials, and classifications of 3D printing technology. Further, the rest of the chapter is organized as follows. Section 12.2 describes the basic principles of 3D printing. Section 12.3 describes the market scope of the 3D printing industry. Section 12.4 contains the applications of 3D printing in various industries, showcasing its positive advancements and transformative potential.

12.2 Basic principles in 3D printing

The basic principles which are used in 3D printing are given below [7]:

a) 3D modeling

3D modeling is described as the process in which a 3D object is created by using 3D modeling programs. When compared to other models, 3D models made with CAD have a relatively lesser number of errors. Manual modeling is used in the preparation of geometric data for 3D graphics. The process of creating a digital model from digital data is known as 3D scanning. The CAD file format used is STL.

b) Printing

3D model made from an STL file can be easily printed. The majority of CAD applications produce STL files that contain some errors like holes, normal, noise shells, self-intersections, errors in manifolds and overhangs. STLs created from 3D scanning models typically have a higher prevalence of errors because 3D scanning is typically carried out through point-to-point acquisition and mapping. In many cases, errors are included in 3D reconstruction. Using “slicer” software, the STL file must be processed after completion to create a G-code file for a particular kind of 3D printer called FDM printers. The G-code document can be printed using the client software.

c) Finishing

The resolution produced by the printer is sufficient enough for many applications. However, printing an oversized version of the desired object in standard resolution and subsequently removing the material using a subtractive process with a higher resolution can lead to greater accuracy. During the building process, the effects are highly influenced by the orientation of a part surface. In the process of making parts, some AM methods can make use of multiple materials. Painting would not necessarily be required because these methods can simultaneously print in multiple colors and different color combinations. For overhanging features, internal supports must be constructed using some printing methods. After the print is finished, these supports must be removed or dissolved mechanically. After deposition, each of the commercially available metal 3D printers involves cutting the metal component from the metal substrate. The removal of aluminum or steel can be accomplished by modifying the surface of the substrate using a brand-new GMAW 3D printing method.

12.3 3D printing industry and market scope

In 2022, the global market for 3D printing was USD 16.75 billion. But from 2023 to 2030, the market is expected to expand by 23.3% [8, 9]. The main reason for the market to expand is aggressive research and development in the field of 3D printing and the

rising demand for prototyping applications from a variety of industry sectors, particularly healthcare, automotive, aerospace, and defense.

The application of 3D printing in manufacturing is referred to as AM. AM is the process of adding material layer by layer to an object using software and a 3D printer. Applying this method to various industry sectors in accordance with the requirements is the final step [10, 11].

Installation services, solutions for consultation, customer support, and management of copyright, licensing, and patenting issues are all part of the deployment. Manufacturers are benefiting in terms of prototyping, structure and product design, and modeling. As a result, production costs have observed significant downfall resulting

Report Attribute	Details
Market Size Value in 2023	USD 20.37 billion
Revenue forecast 2030	USD 88.28 Billion
Growth Rate	CACR of 23.3% From 2023 to 2030
Base year for estimation	2022
Historical data	2017–2021
Forecast Period	20203–2030
Quantitative Units	Revenue in USD milion/billionand CAGR from 2023to 2030
Report coverage	Revenue forecast, company ranking, Comepetitive landscape, Grown fcators and trends.
Segments Covered	Component, printer type, technology, software, application, vertical, material and region
Regional scope	Component, printer type, technology, software, application, vertical, material and region
Country Scope	US, Canada, Mexico, South Korea.

Fig. 12.3: 3D printing market scope [13].

in higher quality goods at reasonable prices. The market scope in 3D printing is described in Fig. 12.3 [12].

12.4 Applications of 3D printing

The fact that 3D printing is a straightforward technology that lends itself to applications in a wide range of fields accounts for a significant portion of the recent increase in its use. 3D printing was expensive to start using at first. Materials and models for 3D printers cost a lot. Costs have been falling in recent years due to technological advancements [14]. Various applications of 3D printing are depicted in Fig. 12.4. These applications are discussed further [15, 16].

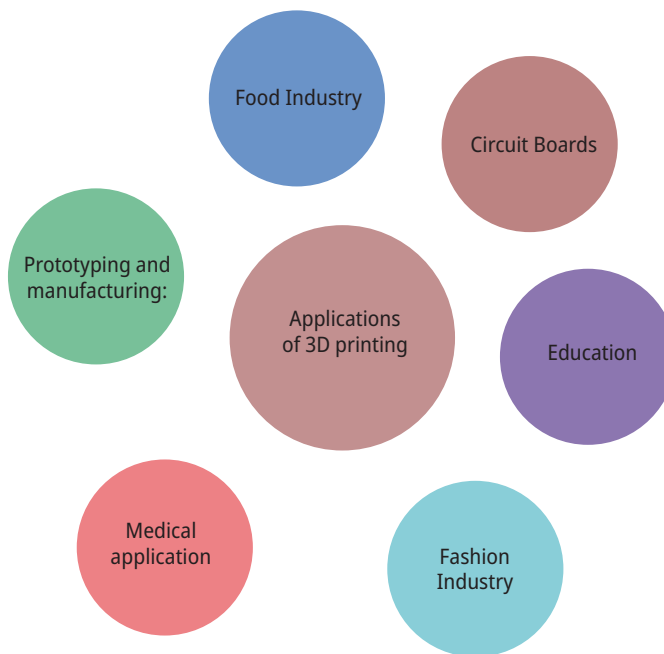


Fig. 12.4: Applications of 3D printing.

12.4.1 3D printing in education

3D printing provides students with an opportunity to participate in the educational process. Even though there are many studies on how different learning styles work and how well different teaching methods work, a lot of traditional education still requires students to memorize reading material. Students can really connect with the material

by manipulating ready-made teaching aids or making their own tools through 3D printing. This results in an increase in students' engagement and participation.

12.4.2 3D printing in prototyping and manufacturing

The initial purpose of 3D printing was to speed up prototype development. It could be costly and time-consuming to make a single mold with a conventional injection-molded prototype [2]. A prototype can be produced with reduced time and cost with the help of 3D printing. The aerospace and automotive sectors are just few examples of manufacturing sectors that are benefited from advancements in 3D printing technologies.

Due to the widespread use of distributed computing technologies today, a number of businesses offer cloud-based services for the production of additional materials. These services allow customers to make parts and items from a distance without having to invest in a 3D printer. Customers can now order unique 3D printed mobile phone cases or other items that have been customized through simple web-based software as part of companies' mass customization services.

12.4.3 3D printing in medical industry

3D printing exhibits an important role in the medical industry [17]. Some of the applications of 3D printing in medical field are shown in Fig. 12.5.

a) **Dental:** While milling from a resin base is labor-intensive and requires multiple visits to a dentist, 3D printing may produce dentures more quickly and at a lower cost. There have been a number of positive indications, despite the fact that the method is not yet perfect due to aesthetic limitations and low-resolution printers: New denture-making materials have recently received the CE mark, which indicates that they are safe for use in the EEA (European Economic Area), and user acceptance of dentures has been demonstrated by patient studies. Form labs already provide customized denture solutions; their site recommends cost reserve funds of over half contrasted with totally processed teeth. The social and economic effects of AM solutions are especially intriguing because 3D printing may be used to make dentures more readily available to those who require them most.

Indirect dental procedures can also be benefited from the use of 3D printing. Even though 3D printing is clearly used to make dental end-use parts like bridges and crowns, copings and substructures, and more, it also helps to make castings. The one who goes through orthodontic treatment had the unpleasant experience of biting into the wax to make the perfect mold. However, 3D printing and scanning produce highly accurate molds.

Not only this, doctors also believed that 3D printing will help 30 million people around the world who needs prosthetics and braces.

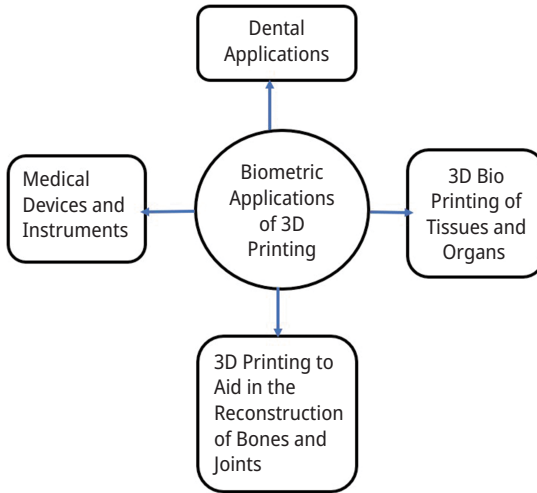


Fig. 12.5: Applications of 3D printing in the medical field.

b) **Medical devices and instrument:** Rapid prototyping and 3D printing have become synonymous terms. Many companies that make medical tools use the technology to make completely new surgical instruments and medical devices. The operation of four Formlabs machines at the moment has a significant impact. Our costs have decreased by 70%, our rapid manufacturing 3D printing rate has doubled, and the level of detail in our prints enables us to clearly communicate designs with orthopedic surgeons. The prototypes were suitable for clinical trials because they resembled finished goods.

When prototypes were produced in-house, overall lead times were significantly reduced by 80–90%. Additionally, the time taken for finishing and painting was a matter of days rather than weeks because printing them only took 8 h [18].

c) **Rebuilding of bones and joints:** A fake bone implant made of 3D-printable ink created by Northwestern University researchers quickly stimulates bone regeneration and growth has been developed. This material for hyperelastic bone can be easily shaped into a variety of shapes especially helpful for treating bone defects in children.

Although bone implant surgery is difficult and painful, especially for children, it is not simple. Bone is frequently extracted from another part of the body in order to replace missing bones in children and adults, which can cause additional complications [19].

d) **3D bioprinting of tissues and organs:** Regenerative medicine is incorporating 3D bioprinting to meet the demand for transplant-ready tissues and organs [20, 21].

Multidisciplinary research has resulted in the design and development of a multi-lateral 3D bioprinting technique that produces vascularized human cell-based tissues which is 10 times thicker than earlier engineered tissues and capable of maintaining

their architecture and function for more than six weeks. The method makes use of a customizable printed silicone mold. A separate print job layers a self-supporting ink that contains the living mesenchymal stem cells into a grid of larger vascular channels printed inside this mold with silicone ink. The larger vascular channels contain living endothelial cells. Afterward, a liquid containing extracellular and fibroblast matrix is used to fill in any gaps in the structure. This helps in strengthening the structure as a whole by forming cross-links [22].

In 2020, new biotechnology [23] research and developments are shaping biomedical engineering. The technology's potential is being demonstrated by significant advancements, despite the numerous obstacles that still need to be overcome [18]. Some of the most notable accomplishments in bioprinting that made 2020 a positive year are:

1. **FRESH-Bioprinted Lifelike Heart Model:** A cardiac model that is durable enough to handle, suture, and perfuse was printed by researchers in the Department of Biomedical Engineering's Feinberg lab at Carnegie Mellon University. Because it resembles the elasticity, feel, and mechanical properties of real cardiac tissue, it is ideal for surgical training and simulation. The cardiac tissue made from soft hydrogels could be printed on a large scale using the Freeform Reversible Embedding of Suspended Hydrogels (FRESH) bioprinting method, which has the potential to be used in surgical training.

2. **Bioprinting Tissue for COVID-19 Research:** WFIRM in North Carolina used a brand-new multiorgan-on-a-chip developed by Anthony Attala to test drugs' toxicity. In a paper that was published in February 2020, Attala and other researchers claimed that the "3D body on a chip" could speed up and increase the profitability of drug development while also lowering the risk of drug withdrawal once a drug is on the market.

The specialist asserted that cell-derived 3D organoid technology may be significantly superior to animal models or cultured cell lines. To repair tissues and enter the body, this platform makes use of an endoscope. The researchers were successful in curing gastric by bioprinting tissue scaffolds with two layers in a stomach model. They used bioinks made of human gastric smooth muscle cells and human gastric epithelial cells in gelatin–alginate hydrogels to resemble the stomach's anatomical structure. The printed cells kept up with high reasonability and consistent expansion following a 10-day culture, showing that the cells in printed tissue platforms carry out a significant natural role. The work represents a novel development in clinical sciences and bioprinting.

3. **Aiding Maritime Ecosystems:** because bioprinting [24] is used for more than just regenerative medicine and tissue engineering. A group of researchers from the University of Cambridge and the University of California, San Diego, created bionic, 3D printed corals in April 2020. As a result, research on coral-algal symbiosis, coral reef conservation, and algal biotechnology can now benefit from coral biomaterials. The coral-inspired photosynthetic biomaterial structures, which were able to replicate the structural and func-

tional characteristics of the coral-algal symbiosis, were created using a speedy 3D bioprinting technique. This opened up new opportunities for coral conservation-related applications of bioinspired materials. Daniel Wangpraseurt, a marine biologist at UC San Diego, said that his work to develop bionic 3D printed corals as a new tool for coral-inspired biomaterials that can be used in algal biotechnology, coral reef conservation, and research on coral-algal symbiosis will benefit greatly from bioprinting technology.

4. Desktop stereo lithography and other affordable and precise 3D printing methods are making the technology more accessible to everyone, encouraging medical professionals to come up with novel clinical solutions and produce individualized devices quickly, and making it possible for doctors to treat patients all over the world [24].

12.4.4 3D printing in the food industry

In the food industry [25, 26], the term “3D printing” refers to the process of creating foods using technology from 3D printing. The food is built up one layer at a time until it is all there. The food [27, 28] is not cooked by 3D printers; rather, it is prepared in the desired form. From that point, they might be cooked on a stove after the printing system is finished. Sugar and chocolate, for example, can be eaten right after printing. The first foods to be 3D printed were:

- a) Chocolate: Chocolate must be stored in a liquid state. After being extruded, it cools quickly, making it an excellent food for 3D printing.
- b) Cheese: Cheese, like chocolate, must be held in its molten state before being extruded. Additionally, it cools relatively quickly.
- c) Cookie dough: Treat batter is a glue that can be handily expelled into the expected shape. However, before the cookie can be eaten, it must be baked in an oven after being printed.

The variety of ingredients that can be printed using a 3D printer is constantly expanding. Some of the most frequently used ingredients are as follows:

- a) Sugar: It is possible to successfully 3D print a variety of sugars, including icing sugar and castor sugar. Binder jetting is a common technique.
- b) Cake frosting: Food-based 3D printing can be used to decorate cakes with icing. With little effort, complex designs can be created.
- c) Dough: When printing with dough, the best consistency is achieved by balancing the ingredients in the right proportions. Dough for pizza crusts can be easily printed.
- d) Systems of hydrocolloids: Ingredients based on gelatin and xanthan gum are these. In order to improve the taste, flavors are added.

- e) Food ink colored: Existing food products can be enhanced with food inks. The ink is set onto the food utilizing an inkjet-style printing innovation.
- f) Meat cultured: A method similar to inkjet printing can be used to print meat cells. Food that looks and tastes like meat without the potential moral repercussions of real meat can be made from both meat and fat cells.

12.4.5 3D printing in fashion industry

As 3D printing enters the clothing industry, the designers are continuously experimenting with 3D printed dresses and shoes. In 2012, Nike's Vapor Laser Talon football shoe was made using 3D printing. With rapid prototyping, glasses can be customized on demand. 3D printing can play a significant role in fashion companies down the road, especially if it transforms into a tool for customers to print it themselves.

12.4.6 3D printing in circuit boards

Imaging, drilling, solder mask coating, and surface finishing are some of the steps that are used for making circuit boards. These means incorporate numerous synthetic substances like unforgiving solvents and acids. While still producing intricate designs, 3D printing circuit boards eliminates many of these steps. The silver polymer [29] is used to make the traces and holes that allow electricity to flow, while polymer ink creates the build's layers. Depending on the design, manufacturing current circuit boards is time-consuming. Lamination tooling is typically punched into the etch cores. The cores can be then prepared for lamination and the stack of a circuit board is prepared and sent to lamination for bonding of layers. Afterward, the boards are then measured and drilled. The material is plated with holes. The exterior image is then printed, developed, and etched. The nomenclature is then added to make it easier to identify components later. After that, the surface finish is applied. After being routed from a panel to an array or a single form, the boards go through an electrical test. After the necessary paperwork to demonstrate that the boards meet specifications has been completed, they are packed and shipped. With 3D printing, the final outline can be defined right away, there is no need to image, punch, or laminate, and the silver polymer used to make electrical connections does not need to be drilled or plated [30].

In addition, 3D printing is used to construct homes, replicate archaeological artifacts, create soft actuators, and many other applications. Because 3D printing is becoming increasingly popular, its applications are also expanding to meet the requirements.

12.5 Conclusion

3D printing technology is one of the fastest growing technologies in the manufacturing process, which slowly changes production and life but also plays an important role in cultural creative designs, industry, and biological and medical fields. As for manufacturing processes companies like Stratasys, Ltd, Desktop Metal Inc., and many more companies are using 3D printing as to gain more profit. The future of 3D modeling is bright because it is still getting more and more used in a lot of different fields. In the coming years, 3D modeling will gain even more significance as new technologies like virtual reality and augmented reality emerge [31, 32]. 3D printing had come forward to change the world. Research is still going on to make more impact for better understanding and usage. Some predictions regarding the future of 3D printing include scalability from rapid prototyping, a more resilient supply chain through digitalization, greater flexibility and more customized design, and creating a more sustainable future.

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13 3D printing insight: techniques, application, and transformation

Abstract: This study provides a thorough examination of 3D printing (3DP) procedures, including conventional and unconventional approaches. It emphasizes the significance of precision and miniaturization in micro- and nanoscale 3DP, allowing for the construction of complicated structures with applications in a variety of sectors. The report also analyzes recent material developments, printing methods, and potential 3DP trends. It presents the notion of four-dimensional printing, which adds the factor of time and enables printed things to change shape and adapt to their surroundings dynamically. The research emphasizes the importance of file formats in 3DP by contrasting conventional formats with advanced formats that provide enhanced capabilities. It also provides insight to the software components of the 3DP processes, such as the process parameters and reason for steppe effect and the requirement for post-processing. Concluding, the study gives significant information for researchers, practitioners, and industry experts navigating the quickly changing field of 3DP and helpful in understanding its capabilities.

Keywords: 3D printing techniques, conventional and non-conventional, printing formats, process parameters

13.1 3D printing

Three-dimensional (3D) printing (3DP), in other terms additive manufacturing (AM), is a cutting-edge manufacturing process where successive layers are printed to construct objects, utilizing a digital 3D model as a guiding blueprint. This technology empowers designers to fabricate intricate and complex geometries that were previously unattainable or exceedingly difficult using conventional manufacturing approaches. By eliminating challenges such as excessive material wastage, limitations in shaping intricate designs, and the necessity for specialized tooling, AM enables designers to achieve unparalleled freedom in their creative endeavors. Consequently, engineers have experienced a substantial augmentation in their design possibilities, owing to the extensive adoption of AM techniques [1, 2].

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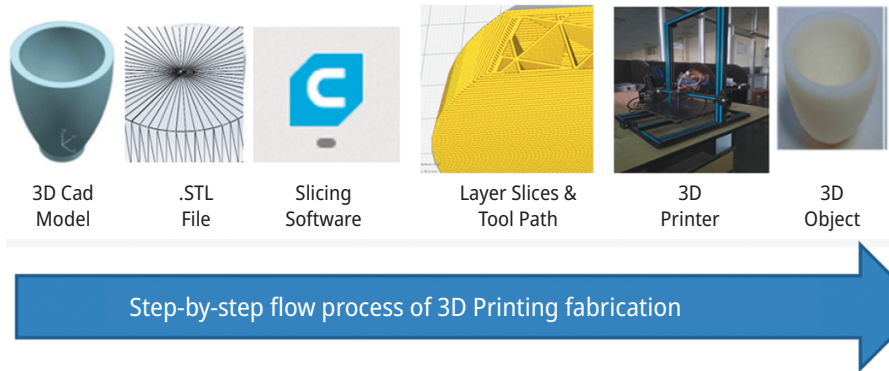


Fig. 13.1: Flow process for object fabrication using 3D printing.

Additionally, the number of parts (fabricating separately) can be decreased, leading to a reduction or elimination of assembly time and cost [3]. Moreover it also specializes in fabricating crucial replacement parts on demand, which improves responsiveness, reduce steps in supply chains as well as storage requirements, put a reduction in delivery costs by shortening lead time [2]. Early applications of AM technology focused on the quick fabrication of prototype models in machine tools and the provision of physical validation in support of continuous product development. However, significant technological improvements over the past decade have broadened the possibilities of AM, allowing it to be utilized for direct manufacturing. It has become an integral part of niche markets served by industries including aerospace, biomedical, and automotive. In subtractive manufacturing, unwanted components are eliminated before the final product is made [4]. AM enables for the fabrication of very complicated and customized objects, which is not possible with traditional manufacturing techniques due to their constraints in making elaborate designs or personalized products [5]. Complex geometries and individualized parts can be created by building them up, layer by layer, using a digital design or model as explained using Fig. 13.1. One of AM's main benefits is that it can be used to make sophisticated, one-of-a-kind items without adding too much time or effort. It allows designers and manufacturers to tackle innovative design challenges and meet specific needs that were difficult or impossible to achieve with traditional manufacturing processes [6].

13.1.1 History

AM has its roots in the 1980s, when a range of technologies emerged that could construct 3D objects directly from digital data files, layer by layer. In the 1980s, AM technology was introduced as a means to produce functional prototypes quickly using different materials to enhance design visualization and assess compatibility with existing parts. Due to the accelerated prototyping process facilitated by these technologies, they became

commonly known as “rapid prototyping” [7, 8]. Dr. Hideo Kodama played a significant role in this development. In May 1980, he filed a patent application for a method that involved solidifying a photopolymer material into a spatial model using ultraviolet (UV) light. Despite efforts to secure funding and support from the government, Kodama was unable to advance the research and development of the patented method. As a result, the patent was ultimately abandoned and never brought to commercialization [9–11].

Charles W. Hull was instrumental in the emergence of 3DP as a commercially viable technology by filing a patent for the stereolithography (SLA) method in 1987. This patent marked a significant milestone in the emergence of AM and led to the co-founding of 3D Systems, Inc., a leading 3D technology corporation. The SLA method utilized photopolymerization, which uses a focused UV light source to cure selectively to build solid objects layer by layer. This process allowed for the accurate representation of the surface geometry of 3D objects [12, 13]. The creation of an eye-wash cup as a consequence of a successful SLA demonstration demonstrates the technology’s potential. Subsequently, 3D Systems Corporation assumed the lead in advancing and refining SLA technology, contributing to the widespread adoption of 3DP across numerous industries. In addition, Hull and Lisa Crump founded Stratasys in the late 1980s through their collaboration. Together, they invented fused deposition modeling (FDM), a technique for fabricating objects involving the deposition of layers of material, and subsequently obtained multiple patents [14–16]. In 1989, Hans Langer, established EOS (Electro-Optical Systems), a company that specializes in the production of 3D parts through a process called metal laser sintering. This method involves using a computer model to guide the laser-based sintering of metal powders into solid objects. Notably, EOS acquired all the patents related to laser sintering under the dual transfer mode in 2004, further solidifying their position in the industry. In the 1990s, Carnegie Mellon University and Stanford University introduced a novel approach to AM. Their method involved the spraying and micro casting of materials, offering a new avenue for creating objects through additive processes. These developments have significantly contributed to the advancement of AM and its application in various industries [13, 17–19].

The 3DP business split in the mid-1990s, with one focus on the manufacturing of complicated and highly engineered parts for medical equipment, and the other on the development of user-friendly printers for economical prototype and concept refining. However, consolidation occurred over time, resulting in the survival of only three major corporations: EOS, 3D Systems Inc., and Stratasys. During that time, these companies stayed at the forefront of the rapidly growing area of 3DP [8].

In the beginning of the twenty-first century, 3DP technology was widely adopted in a variety of commercial settings as a trustworthy method of producing finished goods. The RepRap project, founded and headed by University of Bath researcher Adrian Bowyer, quickly became a major player. The goal of this open-source endeavor was to produce 3D printer as an aim to replicate itself. The purpose behind this is to make 3DP technology more widely available and affordable. The RepRap project was essential in expanding access to and improving the quality of 3DP at the time [20].

13.2 Overview and applications of 3D printing in various sectors of industries

Advanced manufacturing technologies play a crucial role in driving a paradigm shift and have the potential to enhance productivity. Additionally, the significant increase in flexibility enables industries to provide personalized options and reduce overall time to market. With the emergence of new materials processing techniques, manufacturers are continually seeking manufacturing methods that provide greater design freedom. Among these techniques, AM stands out by offering a unique layer by-layer material addition process, providing unparalleled freedom in design. This presents exciting possibilities for the design and production of industrial equipment [21]. At present, AM is being actively employed and explored in various industries, including medical, automotive, aerospace, marine, and industrial sectors. In the medical field, for example, it is utilized for creating patient-specific implants and prosthetics. The automotive industry explores AM for rapid prototyping, customized components, and tooling. In aerospace and marine industries, AM is used for lightweight and complex structures, reducing weight and improving performance. Additionally, AM is also employed for producing industrial spare parts, enabling faster and more cost-effective replacements. The versatility of AM makes it a compelling choice for innovation and optimization across diverse industries [22–25]. The invention of 3DP has garnered significant attention within the field of architecture due to its ability to enable direct manufacturing of parts. AM is experiencing rapid development, with new players continuously entering the market [26]. Significant investments have been made in emerging companies like Carbon, Desktop Metal, and Formlabs, whereas already established huge organizations such as HP and GE are also focusing on utilizing AM for internal development. Although the fundamental principles 3DP remain unchanged, investment is being made for advancement of these technologies. This progression paves the way for the next level of innovation and unlocks new possibilities for industrial applications. The growing interest and investments in AM signify a positive trend toward further expansion and utilization of this transformative manufacturing technology [27–29]. Discussing about electronics parts, extensive studies have been conducted for producing sensors using 3DP technology. Force and motion sensors, hearing, optics, and other fields have been the primary targets of this investigation. Other sensor categories frequently necessitate incorporating commercially available components into 3D-printed structures, although electrical and force sensing modules have shown great compatibility with 3DP techniques. By fusing printing technology with electronic device design, the advent of 3D-printed sensors marks a convergence of key technologies. Substrate boards, electronic ink, and tailored printing methods are key to the advancement of 3D-printed sensors [30].

Metal AM has revolutionized the design and production processes by offering numerous benefits. The benefit of flexible design helps in fabricating optimized as well as durable designs, resulting in lighter as well as similarly stronger products. Addi-

tionally, metal AM allows for faster customization, shorter lead times, and cost reduction. As a result, several automotive companies have started incorporating metal AM into their manufacturing processes. For example, a 3D-printed steering knuckle, or upright, was produced using EOS DMLS technology for the Formula Student Germany 2012 competition. This component showcased a significant weight reduction of 35% compared to the conventional cast part [2]. French luxury carmaker Bugatti has unveiled some remarkable 3D-printed metal components. The 2.9 kg brake calliper, crafted from Ti6Al4V titanium alloy, is a particular marvel. One of the largest callipers ever made, this extraordinary device is intended for use with future automobile models [31]. GE Aviation uses concept Laser and Arcam metal printers to fabricate fuel nozzles for their LEAP engine. These sophisticated printers produce these important components with precision and brilliance [32, 33]. Application can be seen in electrical rotors also [34]. Topology-optimized human implants were developed using lattice architectures in a work by Vilardell et al. SLM EOS M28 printer was utilized to fabricate these Ti6Al4V implants. The study demonstrated that these cutting-edge layouts have the potential to efficiently counteract the stress shielding effect commonly seen in implant applications. This finding is a significant step forward in implantology, since it suggests improved durability, functionality, and longevity for these devices [35]. Revilla-León et al. gone through a comprehensive review of various medical applications of AM. Their study aimed to provide interested readers with insights into the latest advancements and potential uses of AM in the field of healthcare [36, 37]. Study shows diverse application for AM in dental contexts [38].

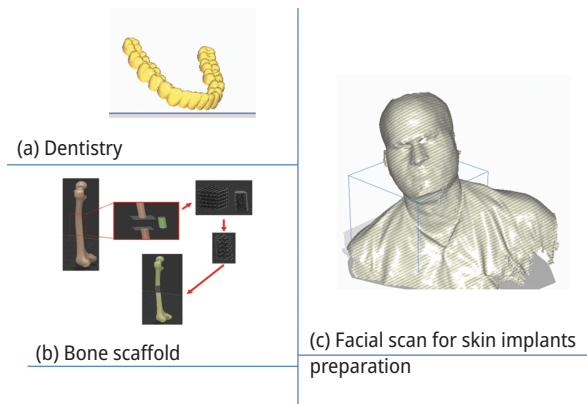


Fig. 13.2: Application of 3D printing in biomedical industry: (a) orthodontic retainer; (b) bone scaffold [37]; and (c) human face scan for skin implant.

The advancements in 3DP technologies offer potential for customized nerve therapies and drug delivery systems, supporting patient-specific healthcare [39] represented as retainer model, facial scan, bone scaffold using Fig. 13.2, reverse engineering for cus-

tomized implants in biomedical [40]. Further developments include four-dimensional (4D) printing (4DP), which introduces dynamic changes in return to stimuli interaction on 3D-printed structures fabricated using smart materials. Smart materials enable printed scaffolds to mimic tissue responses, such as electrical stimulation promoting nerve cell growth and stem cell differentiation. Low-level laser stimulation also shows promise in promoting stem cell differentiation into neurons. Current focus is on the response of cells to external stimuli, with future potential for shape memory functions in 4D-printed nerve conduits, allowing self-adjustment for longer durability. This field holds numerous possibilities awaiting exploration [41–43]. The field of 3DP in medical applications, specifically in skin repair and regeneration, that is, soft tissues, holds immense possibilities for revolutionizing healthcare. The use of natural-based bioinks has shown significant benefits, offering a 3D microenvironment that supports cell adhesion, proliferation, and tissue formation. In vivo studies have demonstrated promising results with successful wound closure and well-organized skin layers. However, further research is necessary to explore different cell types and optimize the properties of bioinks to enhance their therapeutic efficacy. The integration of various disciplines, such as engineering, biology, and medical science, is crucial to overcome challenges in achieving precise tissue details and advancing in situ bioprinting techniques. Novel cross-linking techniques and self-healing hydrogels provide additional avenues for improving structural control and scaffold functionality. With continued advancements in 3DP technologies and bioink development, we can expect exciting advancements in personalized medicine and tissue engineering, leading to improved patient outcomes and enhanced quality of life [44]. A brief summary of applications is represented using Table 13.1.

Tab. 13.1: Summarizing applications in various field of Engineering.

Field	Application	References
Automobile	Buggati Brake calliper, steering knuckle	[2, 31]
Electronics	3D-printed sensors	[30]
Aerospace	Fuel nozzles, metal additive	[32, 33]
Biomedical	Dental implants, bone implants	[27, 38–40]
Shape-memory polymers	Stimuli-responsive application	[41, 42]
Tissue engineering	Skin repair	[44]

13.2.1 Application in micro- and nanomanufacturing: implications and advancements in fields like microelectronics, micro-optics, lab-on-a-chip devices, and nanomedicine

Electronics, motion sensing, hearing, and optics are just few of the areas that are more focused in recent studies. Particularly promising is the interoperability between 3DP and electrical and force sensor devices. Important fields like printing and elec-

tronic device design come together in the field of printed sensors [30]. Miniaturized automated laboratories, or “lab-on-a-chip” (LOC) devices, combine several biochemical processes into a single device. Clinical diagnostics are one important area where these systems can be used. There are a number of benefits to using LOC devices instead of conventional diagnostic approaches. Because of their low sample volume requirements, low reagent costs, and potentially increased sensitivity, these assays are ideal for point-of-care diagnostics. These gadgets have minimal electronic noise and embedded computing capabilities, and they are small, portable, modular, and reconfigurable. Their low power consumption and simple integration make them ideal. Reliable findings can be obtained with LOC devices since they reduce the chances of human mistake and contamination. They improve the usefulness and durability of devices by facilitating a number of processes with a minimum number of moving parts [45–47]. MEMS, short for microelectromechanical systems, refer to small-scale devices that integrate electrical and mechanical functionalities [48]. Common examples of MEMS include pressure sensors, gyro sensors, accelerometers, and inkjet heads [49]. MEMS have garnered considerable interest in numerous electronic fields, such as measurement technology, micro-fluidics, and Internet of Things (IoT). In devices like smartphones and autonomous vehicles, MEMS components frequently function as sensors or actuators. MEMS solutions have been created for a variety of applications, but their fabrication process is less standardized than that of microelectronics. However, 3DP offers potential as a solution. Although the majority of 3DP technologies lack the required resolution for MEMS production also commonly used materials for 3DP found unsuitable. There are niche applications where 3DP enables the creation of novel structures and facilitates the faster, more cost-effective production of MEMS systems. This provides opportunities for inventive MEMS applications and improved manufacturing processes [50].

Nanomanufacturing and nanopatterning technologies that are efficient and adaptable are essential for the production of nanotechnology-based products. Current research in these fields concentrates on the development of nanomanufacturing platforms that can produce diverse structures and patterns for device and system integration. Through its SNM (scalable nanomanufacturing) solicitation, which seeks to ease the translation of lab-based discoveries to commercial applications, the National Science Foundation (NSF) is actively engaged in establishing fundamental principles for SNM. In addition to continuous roll-to-roll processes, top-down/bottom-up techniques, scaling-up strategies include large-scale 3D DNA nanofabrication [51]. These developments include a vast category of materials and nanomanufacturing techniques providing potential in numerous fields [52]. Science and engineering have focused on micro- and nanostructuring for decades [53]. SNM technologies aim to reduce feature sizes, increase material flexibility, reduce restrictions, improve process efficiency, and increase dimensional complexity. Using recent advances in micro-nanoscale fabrication processes, studies concludes SNM CAD/CAM system requirements. A process knowledge database, standardized processing algorithms, effective communication routes, adaptive interpolation

techniques, consistent coordinate systems, and efficient peripheral device management are needed. Hybrid and bridging technologies can extend process capabilities, making SNM possible, presenting a nanoscale hybrid 3DP CAD/CAM system. This technique uses aerodynamically focused nanoparticle printing, focused ion beam milling, micromachining, and spin-coating to manufacture full 3D structures from inorganic materials at 50 nm. The network-based platform connects users and process operators, bridging gaps between processes and resources [54]. Prototyping and 3DP have made nanometer- to multimeter-scale items possible. Printing process determines shape accuracy and resolution. FDM can reach 100 μm resolution, while SLA and DLP can reach a few micrometers. As accuracy rises, printing speed decreases, and it may take several days to create nanoscale parts. Biocompatible and hydrogel materials are expanding material availability [55].

13.3 Advantages and disadvantages of 3D printing

The advantage of AM techniques is that once the parts are fabricated, they require little to no additional processing beyond the initial fabrication stage. As a result, the parts made using these techniques can be put to use straight away in mission-critical functions. Directly creating functional parts with the correct specs and surface finish is possible with AM processes, whereas with traditional manufacturing methods, extra steps such as machining, polishing, or assembly are often required. This streamlines the production process, reduces lead times, and eliminates the need for secondary operations, resulting in significant time and cost savings. The ability to obtain finished parts directly from the AM process enhances efficiency and supports the rapid deployment of components in various industries, including aerospace and automotive [56–58].

The manufacture of sensors using 3DP technology is growing in popularity. The ability to halt and resume the 3DP process is a perk that allows for the incorporation of different manufacturing techniques or the usage of traditional manufacturing to build subcomponents. This allows for the uninterrupted production of sensors that are 3D printed, whether they are fully printed or embedded into a printed structure [59]. The introduction of 3DP technology has caused a paradigm change, providing a new direction to manufacturing sector, changing the way that many things are done, including design fabrication, time and cost management. The decrease in production costs is a significant benefit of 3DP. It allows for a streamlined, one-step manufacturing process, as opposed to traditional methods that require labor and several machines to manufacture a product, which in turn results in decreased costs and quicker production times. Rapid prototyping is area where 3DP has found success, as it paves the way for more complex and versatile ideas to be developed [60, 61]. When compared to traditional methods, 3DP has drastically cut down on waste. This is, one of

many reasons, because of the fact that it eliminates the need for molds, which significantly reduces waste and maximizes material efficiency. Because of this adaptability, a wide variety of goods can be made, serving both simple and complex needs. Using computerized software and a 3D printer has made the process more user-friendly, making it available to a wider audience. In conclusion, 3DP is a greener and more efficient method of manufacturing because it results in less waste and greater availability of the final product [62].

While 3DP technology offers numerous benefits, its limitations must be acknowledged. Due to limited material options and the need for precision temperature control, specific polymers cannot be utilized in the printing process. In addition, the relatively small build size of 3D printers necessitates the manufacturing of larger products in separate pieces, resulting in increased costs and assembly complexity. 3D printers' automation

Tab. 13.2: Advantages and disadvantages of 3D printing.

Advantages	Disadvantages
1. Parts made using AM techniques require little to no additional processing, allowing them to be put to use immediately in mission-critical functions [56]	1. Limited material options and precision temperature control exclude specific polymers from the printing process and not suitable for mass production [63].
2. AM processes enable the direct creation of functional parts with correct specs and surface finish, eliminating the need for extra steps in traditional manufacturing methods [57].	2. Relatively small build size of 3D printers necessitates manufacturing larger products in separate pieces, increasing costs and assembly complexity [63].
3. Streamlined production process, reduced lead times, and elimination of secondary operations result in significant time and cost savings [58].	3. Automation of manufacturing processes with 3D printers poses a threat to low-skilled manufacturing employment [63].
4. Obtaining finished parts directly from the AM process enhances efficiency and supports rapid deployment in various industries [58].	4. Inaccuracies may be introduced by 3D printers with lower tolerance levels, requiring post-processing and maintenance, indirectly increasing production costs [63].
5. Ability to halt and resume 3D printing process allows for incorporation of different manufacturing techniques and uninterrupted production of sensors [59].	5. Copyright concerns arise due to the difficulty in distinguishing comparable products produced by different individuals [63].
6. Decreased production costs, one-step manufacturing process, and quicker production times are significant benefits of 3D printing [60].	
7. 3D printing enables rapid prototyping, facilitating the development of complex and versatile ideas [61].	
8. Drastic reduction in waste due to elimination of molds, maximizing material efficiency [62].	
9. Wide variety of goods can be made, serving both simple and complex needs. User-friendly process and accessibility to a wider audience [62].	

of manufacturing processes poses a threat to low skilled manufacturing employment. Inaccuracies may also be introduced by 3D printers with lower tolerance levels, necessitating post-processing and maintenance, which indirectly increases production costs. Finally, the accessibility of 3DP technology raises copyright concerns, as it becomes increasingly difficult to distinguish comparable products produced by different individuals [63]. A brief summary of advantages and disadvantages is represented using Table 13.2.

13.4 Categories of 3D printing

AM procedures are classified according to the material format employed and the applied heat source. There are various forms of feedstock, such as wire, filament, sheet, granules, and liquid. Material composition, chemical properties, and transformation characteristics determine the thermal path and energy consumption in each process [64]. Various AM techniques, such as FDM, SLA, DLP, SLM, binder jetting, and material jetting, enable the production of complex shapes and structures from a wide variety of materials and composites [65].

13.4.1 Overview of commonly used 3D printing conventional techniques

13.4.1.1 Stereolithography (SLA)

SLA printer works by immersing a platform in a tank of light-sensitive resin. Using a sliced STL file as a guide, the printer uses a laser beam to outline the desired shape and harden the resin. The layer height is then used to determine the vertical displacement of the platform. The 3D model is built up layer over layer until desired objective is achieved as shown using Fig. 13.3(c). The standard layer thickness is between 12 and 150 μm . The typical print speed for a SLA printer is between 10 and 20 mm/h. Spot size, or laser beam diameter at the resin to be fabricated, is crucial to the accuracy of SLA printing. A Formlabs Form 2 SLA printer, for instance, has a spot size of just 140 μm [66].

13.4.1.2 FDM (fused deposition modeling)/FFF (fused filament fabrication)

Fused filament fabrication (FFF) has attracted a great deal of interest due to its distinct benefits, which include material versatility, environmental benevolence, affordability, portability, and high precision. CAD data is utilized and sliced by software to generate tool trajectories that guide the movement of the nozzle head and build plate, fabricating to physical object. A nontoxic thermoplastic filament with a lower melting

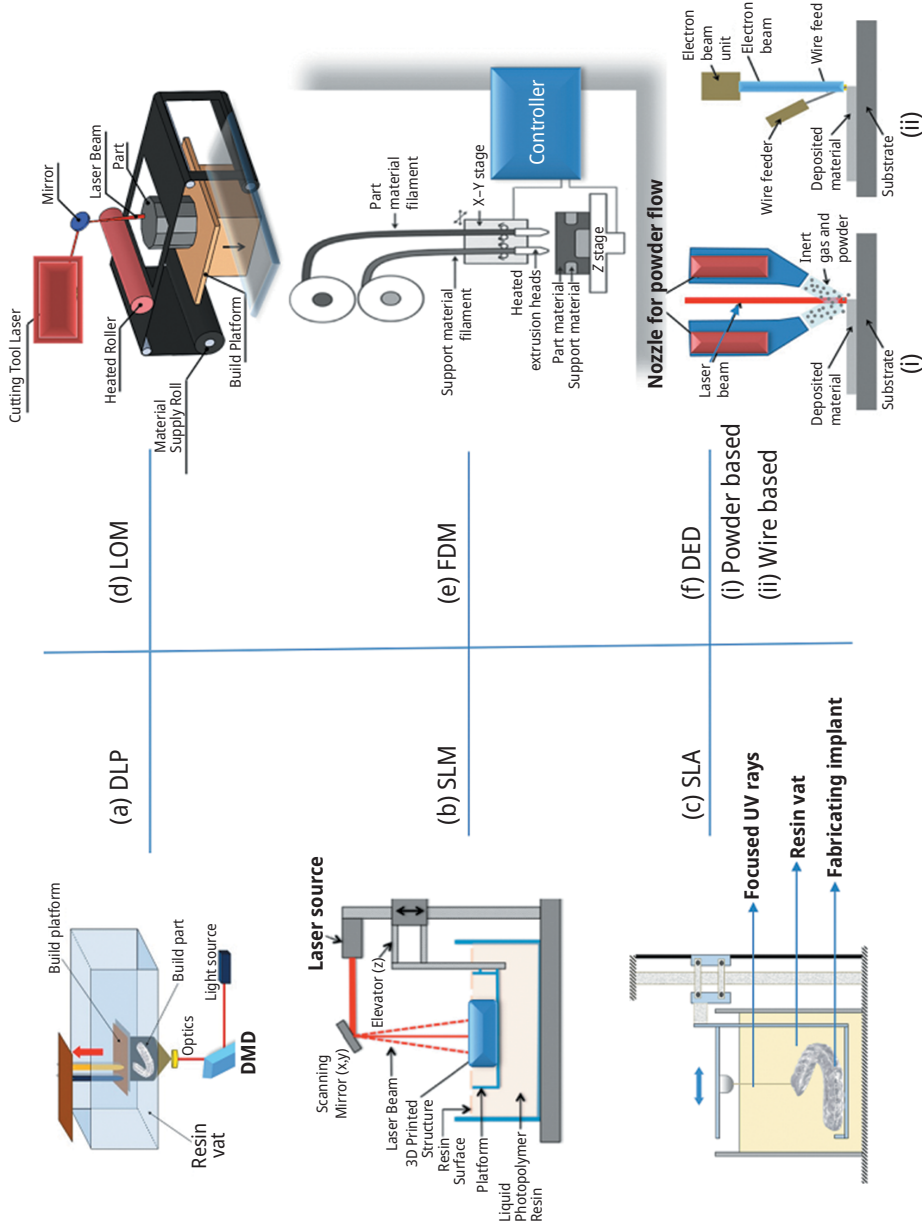


Fig. 13.3: 3D printing techniques.

point is fed into the nozzle head, can be understood using Fig. 13.3(e). The heaters first made wire into a semimolten filament by heating it. The nozzle then deposits filament in the X and Y dimensions on the build platform, which moves downward (in the Z direction) with each successive layer. FFF allows for the production of customized products with minimal advance time and production costs. However, researchers have been interested in the mechanical robustness of FFF parts, as there can be significant variations in mechanical properties due to design differences. FFF parts' relatively lower mechanical strength can restrict their applicability in certain disciplines. Thus, intelligent optimization tools that can predict and maximize the mechanical strength of FFF components are required. Recent research has shifted from focusing predominantly on optimizing process parameters to developing mathematical tools or algorithms to optimize and predict the mechanical strength of FFF parts [67].

13.4.1.3 Selective laser melting (SLM)

Selective laser melting (SLM) is a technique for manufacturing metal objects by melting metal powder layers using a laser beam. SLM entirely liquefies the deposited powder material, resulting in exceptional mechanical properties. There arises the problem of oxide formation in open atmosphere, so to prevent these surface oxides on the molten layers, the operation is conducted in a vacuum atmosphere. Through the application of a laser beam, the metal powder is elevated above its melting point, resulting in a small molten region known as the “melt pool.” This pool of molten metal corresponds to the 2D projection of the CAD model, which guides the exact construction of the metal object. The working principle of SLM is shown in Fig. 13.3(b). SLM focuses predominantly on certain metals, including steel, aluminum, and titanium. SLM's capacity to completely liquefy the deposited metal particles contributes to the superior mechanical properties of the material. SLM's ability to produce high-resolution and high-quality components is a significant advantage, making it particularly advantageous for applications in the aerospace industry, where precision and performance are crucial [14].

13.4.1.4 Digital light processing (DLP)

Digital light processing (DLP) is a technique that produces 3D objects by curing a photopolymer resin, similar to SLA. The primary distinction, however, resides in the light source used. DLP printers utilize projection technology, having short-wave light, typically ranges from 380 nm to 405 nm in wavelength and is directed through a digital micromirror device (DMD) as shown in Fig. 13.3(a), which is central component of DLP. This DMD is formed as a result of many square micromirror having an edge length of approximately 16 μm . By manipulating these micromirrors with electrostatic

fields, light is either optically directed onto the build platform in a translucent container of photopolymer (photopolymer bath) or onto a diffuse surface (absorber). The build platform after solidifying one layer moved along the z-axis as new material for exposure with the subsequent mask flows in. With DLP technology, the amount of time necessary to construct an object is almost unaffected by its size or complexity. Instead, the critical factor is the object's dimension along the z-axis. Each micromirror corresponds to a single image point or pixel, and the precision decreases as the x and y dimensions of the construction platform increase. However, there are methods for achieving larger build platforms, although they may not be economically viable for standard laboratory printers [68].

13.4.1.5 Laminated object manufacturing (LOM)

Laminated object manufacturing (LOM) in 3DP entails building objects using thin sheets of material, layer by layer. A stack of these sheets, typically made of paper or other materials, is bonded together to create a solid block. The intended shape is then cut from the block using laser cutting or CNC machining techniques. Typically, the sheets are coated with an adhesive, and each layer is selectively adhered to the layer beneath it to form the object's geometry. Depending on the specific lamination technique employed, the bonding can be accomplished by a variety of means, including heat, pressure, ultrasonic welding, or adhesive bonding. LOM is based on the sequential lamination and cutting of sheets to progressively construct an object as shown in Fig. 13.3(d). The final 3D object is formed by cutting each layer according to the design specifications and adhering them together. This method permits the creation of intricate shapes and structures. While LOM is commonly associated with the use of paper sheets, other materials such as plastic and metal sheets can also be laminated in a similar fashion. The selection of materials is determined by the intended properties and functions of the end product. In 3DP, the LOM principle entails layering and adhering thin sheets of material to progressively build a solid object, resulting in a cost-effective and versatile AM process [69].

13.4.1.6 Directed energy deposition

Directed energy deposition (DED) is based on the delivery of material in powder or filament form into a localized melt pool created by a heat source, typically a laser. The material is melted by the heat source and deposited onto a substrate or previously deposited layers. This method permits the precise addition of material in order to construct a 3D component layer by layer. In powder-based DED, a bed of powder is distributed across the work area, over it energy is supplied that melts the powder capturing desired shape. After one layer gets fabricated, a fresh layer of powder is sup-

plied to the working zone, and provided with energy. This process is repeated until the component is achieved explained using Fig. 13.3(f). In wire-based DED, the material is introduced directly into the melting pool produced by the heat source. To construct the desired shape, the wire is melted and fused with the substrate or previously deposited layers. DED enables the creation of high-resolution features and dimensional control. It provides a rapid deposition rate, minimal material waste, and minimal distortion. DED can also be used for coating applications such as for corrosion resistance with strong metallurgical bonding between the coating material and substrate material. DED is a cost-effective method that conserves materials and enables fabrication of near-net shape. It is capable of producing monolithic metal parts as well as functionally graded components and can be used to repair and remanufacture high-value components. Numerous industries, including aerospace, defense, and automotive, have effectively implemented the process, which offers geometry flexibility [70].

13.4.2 Nonconventional 3D printing methods: exploration of alternative techniques beyond conventional methods for nanoscale 3D printing or multimaterial printing

13.4.2.1 Binder jetting (BJG)

Binder jetting (BJG) technique was developed in the 1990s at the Massachusetts Institute of Technology (MIT). While its commercialization required some time, BJG technology is now capable of managing a variety of materials, including metals/alloys, ceramics, and even color printing. A metal or ceramic-based powder and a liquid binder are used to bond the powder together within and between layers. Based on the CAD paradigm, the BJG process involves spreading metal or ceramic powder and depositing a binder layer on top of the powder layer as shown in Fig. 13.4(a). This procedure is repeated to progressively construct the component. Nevertheless, BJG requires additional post-processing stages, including curing, de-powdering, sintering, infiltration, annealing, and finishing. Especially sintering, these post-processes can be time-consuming and expensive. A benefit of BJG is its capacity to manufacture components without the need for support structures. The loose powder bed functions as a support, allowing multiple sections to be stacked with minimal gapping. In contrast to conventionally sintered parts, however, the use of binders in BJG can result in porosity, making the parts less suitable for structural applications in industries such as aerospace and automotive [71].

13.4.2.2 Material jetting

Material jetting (MJ) processes are known by two distinct names, due to naming rights held by MJ printer manufacturers Stratasys (called PolyJet) and 3DSYSTEMS (called MultiJet). In 2000, Objet Geometries Ltd. pioneered the development of MJ technology, which was subsequently acquired by Stratasys in 2012. In MJ, photopolymer materials are stored in tanks that exclude air and are selectively deposited onto the construction platform as droplets. The photopolymer is heated in a transmission line prior to being sent to the nozzle, where a very thin layer is ejected. The molten material is then exposed to UV radiation to induce curing as in Fig. 13.4(b). This photopolymerization technique uses a specific wavelength of light to coagulate liquid monomers or oligomers. Unlike other AM technologies such as SLA and DLP, MJ permits a theoretically unrestricted range of wavelengths for the light source, although practical implementations typically use wavelengths between 190 and 400 nm. After each layer is cured, the construct platform is lowered by a predetermined layer thickness, and a new layer of liquid material is jetted onto the previous layer. This procedure is repeated until a complete component is created. Due to the use of liquid or molten materials in MJ, support structures are frequently required, especially in overhanging areas. These support structure can be removed by techniques like sonication in a sodium hydroxide solution, or using high-pressure water streams from the final product [72].

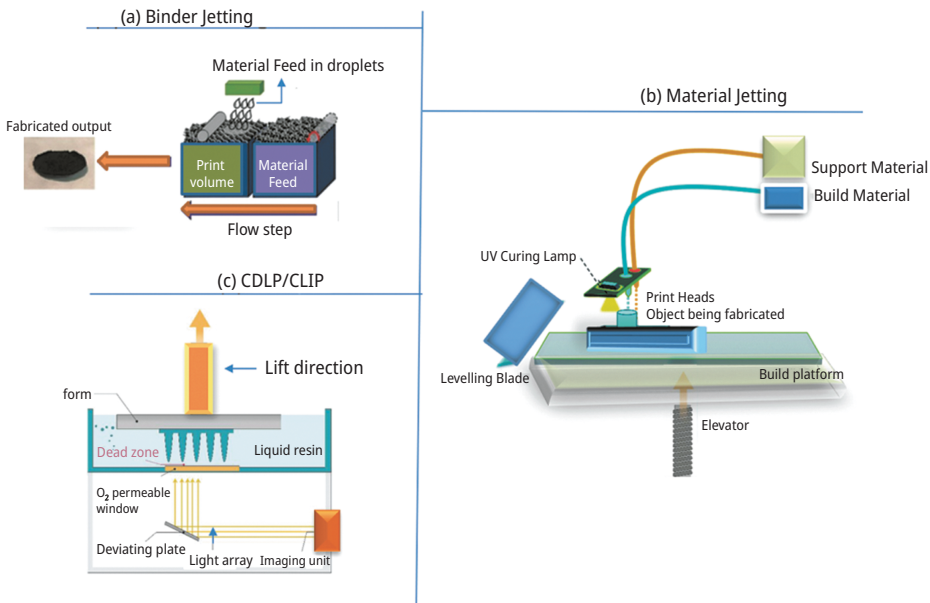


Fig. 13.4: NC 3D printing techniques.

13.4.2.3 CDLP/CLIP (continuous digital light processing/continuous liquid interface production)

Continuous digital light processing (CDLP)/continuous liquid interface production (CLIP) technology is an innovative development founded on DLP principles. Analogous to SLA and conventional DLP, CDLP/CLIP uses digital projection with LEDs and differentiated by an oxygen-permeable window in place of conventional glass window. This window creates a thin layer, known as a “dead zone,” that allows liquid resin to pass between the printed part and the window interface as explained in Fig. 13.4(c). This flux of uncured resin improves the object’s resolution and reduces the risk of printing failure due to peeling forces. Similar to other printing techniques, layer fabrication principle is same, differ by integration of continuous platform movement. This method of printing permits the printing of prototypes at rates of several hundred millimeters per hour without interruption. By eliminating the issue of layer connection (bonding) and minimizing the commonly observed “staircase effect” in other 3DP methods, the continuous printing process in CDLP/CLIP technology generates fabricated parts with isotropic mechanical properties, despite their apparent anisotropy. The CDLP/CLIP technology has multiple applications, including the 3DP of supramolecular hydrogels [66].

13.5 Support structures, staircase effect, and other defects in 3D printing

Support structures are commonly required throughout the fabrication process to give design support at elevated material temperatures, which might result in decreased surface quality as shown in Fig. 13.5. The normal method involves using computer-aided design (CAD) software to create a model, which is then stored as an STL file representing an approximate triangulated model, made up of coordinate(corner) points. To assist construction, the model is separated into layers using slicing software can be seen in Fig. 13.10. While this triangulated model accurately portrays linear shapes, contour shapes may exhibit a subtle staircase effect as seen in Fig. 13.6 circled view, emulating the desired look. Depending on the printing procedure, the 3D printer subsequently deposits materials in a 3D space (x , y , and z). These advancements have transformed the possibilities and adaptability of 3DP technology [73]. Some other defects include improper adherence of layers and nanoscale cracks [21].

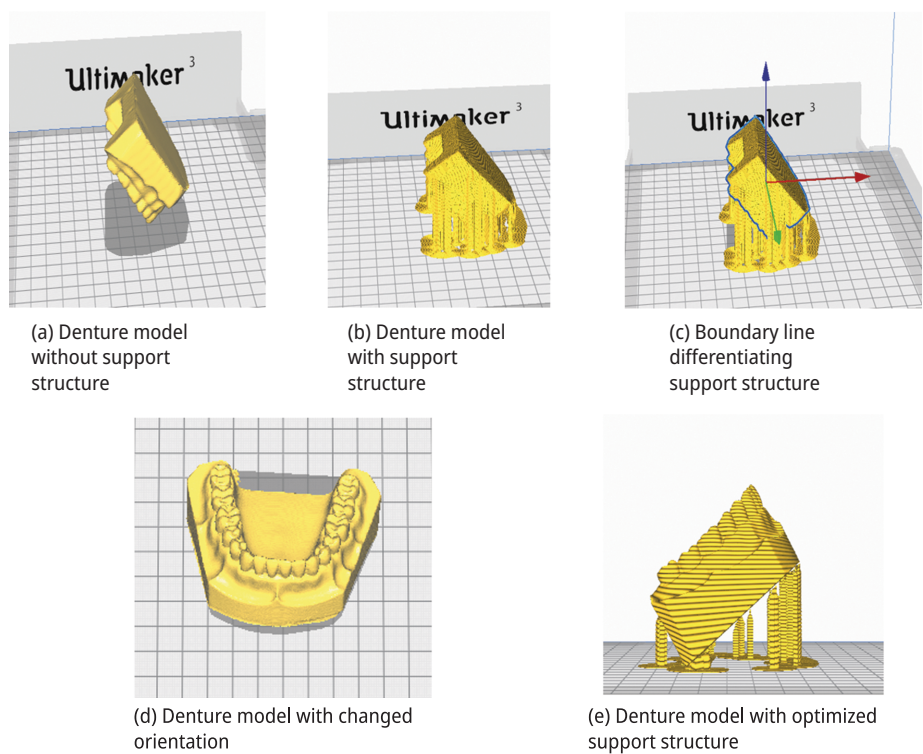


Fig. 13.5: Support structure and its optimization.

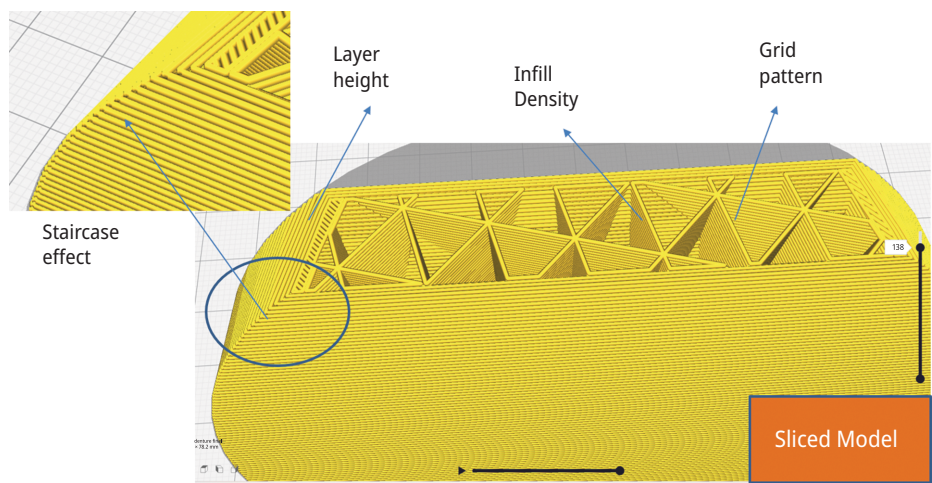


Fig. 13.6: Figure depicting variation points affecting accuracy.

13.6 Introduction to 4D printing: explanation of the concept of 4D printing and its relationship to 3D printing

The advent of 4DP has introduced a ground-breaking approach that leverages AM technology and programmable materials to bridge the gap between the virtual and physical realms [74]. This transformative capability enables the conversion of digital information into tangible objects, unlocking new possibilities for innovation and unprecedented functionality. With 4DP, we can harness the potential of AM and programmable materials to create dynamic and adaptive structures that respond to external stimuli as explained using Fig. 13.7, further expanding the horizons of manufacturing and design [75].

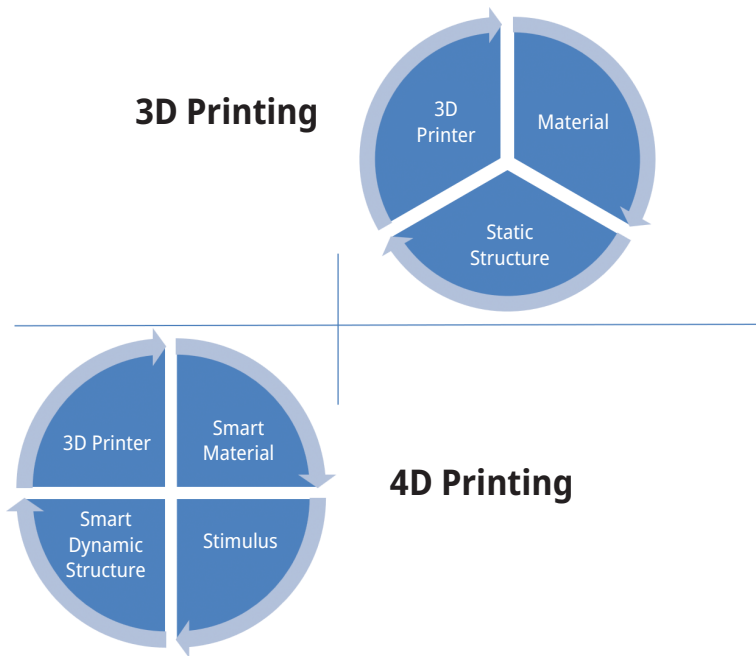


Fig. 13.7: 4D printing: modification in 3D printing [76].

The concept of 4DP, which was first suggested by the Tibbits group at MIT in 2013, has sparked widespread research and exploration across a wide range of areas, including materials, 3D printers, stimulation mechanisms, novel design concepts, and practical applications. Since its inception, significant resources have been committed to understanding and improving the possibilities of 4DP. This continuous research is an exciting opportunity to find new possibilities in production, design, and a wide range of application sectors [77]. By integrating the dimension of time, 4DP has given a novel

feature to AM. This novel approach enables things to change their shape, characteristics, or functionality dynamically over time. Static 3D-printed items can be converted into predictable structures capable of adapting and responding by using stimuli such as light, humidity, pH, solvent, magnetism, electric response, or tension/compression as explained using Fig. 13.8. This advancement in 4DP technology provides the door for the construction of adaptable and responsive objects with broad applications in industries such as biomedical engineering, robotics, and others [78].

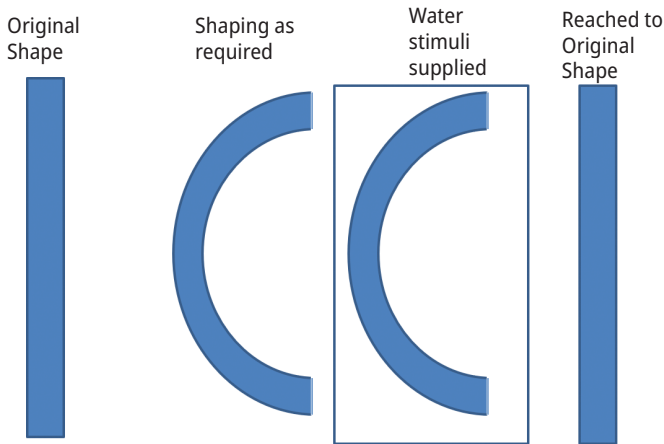


Fig. 13.8: Explanation of 4D printing: shape reformability [79].

In their study, Momeni et al. outlined the five essential elements of 4DP: the 3DP facility, stimulus-responsive materials or smart materials, stimulus, mathematical modeling, and interaction mechanism. They characterized 4DP as the process of deforming stimuli-responsive active smart materials into diverse shapes in response to an external stimulus. This concept emphasizes the dynamic and adaptive aspect of 4D-printed items, which have tremendous promise for applications in engineering, healthcare, and other sectors [80]. Yang et al. and Momeni et al. explored different mechanisms and stimuli involved in 4DP. Yang et al. focused on thermo- and hydro-mechanics, while Momeni et al. discussed eight mechanisms related to 4DP. This summary will specifically focus on the four stimuli: heat, water, pH, and optical mechanics, and their associated deformation mechanisms in polymers [80, 81]. When subjected to temperature fluctuations, thermo-responsive polymers exhibit alterations in elasticity and entropy. When the temperature exceeds the glass transition temperature (T_g) of a polymer, the original orientations of the polymer chains are altered, resulting in the formation of new interactions between adjacent chains. By cooling the material below its T_g , the deformed shape can be fixed so long as the newly formed interactions remain stable, enabling the material to retain its transient shape. Hydro-active polymers, on the other hand, are made up of expandable hydrophilic elements and inactive rigid elements.

These polymers can actively alter their morphology in response to moisture or water. Typically, the shape change can be undone by removing moisture or drying out the polymers. With special design considerations, however, polymers can be programmed to maintain irreversible shapes even after moisture removal. Understanding these stimuli and deformation mechanisms in polymers is essential for the development of responsive and functional materials for 4DP. It opens up a vast array of application possibilities in a variety of fields [82–84].

13.7 Printing file formats in 3D printing

On a wider scale, the use of the STL file format was prevalent in 3DP due to its widespread support in software and hardware [85]. It was noted that 3DP technology had become more accessible and affordable for small and medium-sized businesses, expanding its application. For this other readable file formats are also discussed [86].

13.7.1 STL

STL, or Standard Tessellation Language, is a file format utilized primarily by SLA CAD software, such as that created by 3D Systems Inc. It is utilized extensively in rapid prototyping and computer-aided manufacturing and is compatible with numerous software applications. An STL file contains surface geometry information for a 3D object, represented as a mesh of triangles as shown in Fig. 13.9(a). However, it lacks attributes such as color and texture that are typically present in CAD models. The file format can be stored in either ASCII or Binary format, with binary's reduced file size making it more popular. In an STL file, the geometry of each triangle is specified by the unit normal (a vector perpendicular to the triangle) and the triangle's vertices. Following the right-hand rule, the order of the vertices determines the orientation of the triangle in 3D space. Some software programs, such as VisCAM and SolidView, attempt to circumvent the limitations of the native STL format by storing 15-bit RGB color information in additional bytes at the conclusion of each triangle. The STL file format has a number of inherent flaws. First, it results in large file sizes, which make storage and transmission difficult. Second, the file's security is inadequate, making it susceptible to unauthorized modification or access. Thirdly, the format cannot detect or correct errors, specifically unintended gaps in the part being constructed. It is anticipated that new file formats will eventually supplant STL for transferring data from CAD programs to 3D printers due to these limitations [87].

However, it was recognized that STL files had certain limitations when transferring data from CAD packages to 3D printers. It was anticipated that new formats would eventually replace STL files to overcome these limitations.

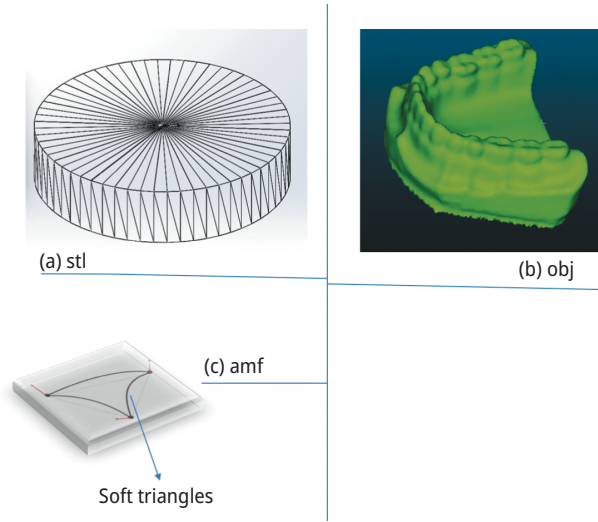


Fig. 13.9: Readable file format.

13.7.2 OBJ

The native STL file format used in 3DP lacks the ability to store color information, making the OBJ format preferred for multicolor printing. Originally used in 3D graphics, the OBJ format gained popularity in the 3DP community due to its open source license and simplicity. OBJ files support both ASCII and binary encodings and can encode geometry, color, materials, and textures [87]. Similar to STL, the OBJ format uses tessellations with polygons to depict the surface of an object as depicts in Fig. 13.9(b). It also permits for more complex schemes, such as curves and surfaces of free form. The format can store color and texture information in a companion file format known as MTL (Material Template Library), allowing for the rendering of multicolored, textured models. However, the OBJ format is more complex than STL, and it can be difficult to restore damaged OBJ files. It also requires the presence of both OBJ and MTL files, which can contribute to confusion and file loss in high-volume production environments [87]. While the OBJ format offers advantages for multicolor printing, it is not as widely supported as the STL format [86].

13.7.3 AMF

The ASTM Committee on AM Standards (F42) recognized the limitations of the STL file format and initiated efforts to recommend a new standard called STL 2.0. In 2011, the AMF 3D printer file format was introduced as a replacement for STL, addressing its

shortcomings. While the AMF format offers technical superiority, it has been slow to be adopted by 3DP industry [87]. The AMF format supports geometry, scale, color, materials, lattices, duplicates, and orientation as shown using Fig. 13.9(c). It is based on XML. It addresses the limitations of the STL format by providing a hierarchical structure for five elements: object, material, texture, constellation, and metadata. The XML format facilitates readability, composition, and processing. Similar to STL, AMF uses triangular meshes to define the surfaces of objects, with the addition of curved triangles. This enables the depiction of curved surfaces without an excessive number of facets, resulting in files with smaller sizes. AMF supports contemporary 3DP specifications such as RGBA colors, graded colors, texture mappings, mixed and graded materials, microstructures, substructures, and porous materials. The AMF format also permits the specification of design scale in a variety of units, alleviating a significant source of aggravation for STL users. In addition, it contains extensive metadata elements, including name, author, company, description, volume, and tolerances, among others. AMF became an ISO standard in 2013. Although the eventual replacement of the STL format is certain, it is uncertain whether Microsoft's AMF or 3MF format will become the dominant standard [87].

13.7.4 3MF

The primary weakness of the AMF format was not its technology, as it effectively addressed the shortcomings of the STL format. The real challenge lied in industry adoption. The developers of the AMF standard, ASTM, did not consult key players in the 3DP industry, resulting in a slow uptake by major brands. Microsoft adopted a different approach when developing the 3MF (3D Manufacturing Format) file format for 3D printers. They worked internally to create a seamless and high-quality experience for consumers and manufacturers of 3DP. Microsoft announced the 3MF Consortium in 2015, with prominent 3DP companies as founding members. The 3MF format, which is based on XML, prioritizes human readability for development simplicity over binary performance improvements. It uses triangular meshes similar to STL but in a format that is more compact and space-efficient than AMF. Notably, the 3MF format efficiently represents multiple identical objects by referencing the same mesh. Similar to AMF, it can encode information about color, material, and texture. The 3MF format's degree of freedom and open-source nature is the primary concern. The 3MF Consortium intends to develop a "plug and play" 3DP tool that minimizes the annoyances associated with poor geometry, model repair, and print failures [87].

13.8 Software aspects of the 3D printing workflow

Software is a crucial component in 3DP, as it controls the process parameters and converts the desired object into specific instructions for the printer. However, variations in the software can lead to accuracy issues and impact the final output of the printing process. Slicing errors can occur during the slicing process, where the 3D model is converted into printable layers and G-code instructions are generated. These errors can result in missing or misplaced layers, incorrect tool paths, or incomplete representations of the object. One common challenge in 3DP is the “staircase effect” (Fig. 13.6), which is observed in contour surfaces. This effect stems from the standard triangulation file format (e.g., .stl) that generates corner or coordinate points for creating G-code instructions. As a result, the smoothness of contour surfaces can be compromised, leading to a loss of accuracy in the printed object that needs postprocessing [88].

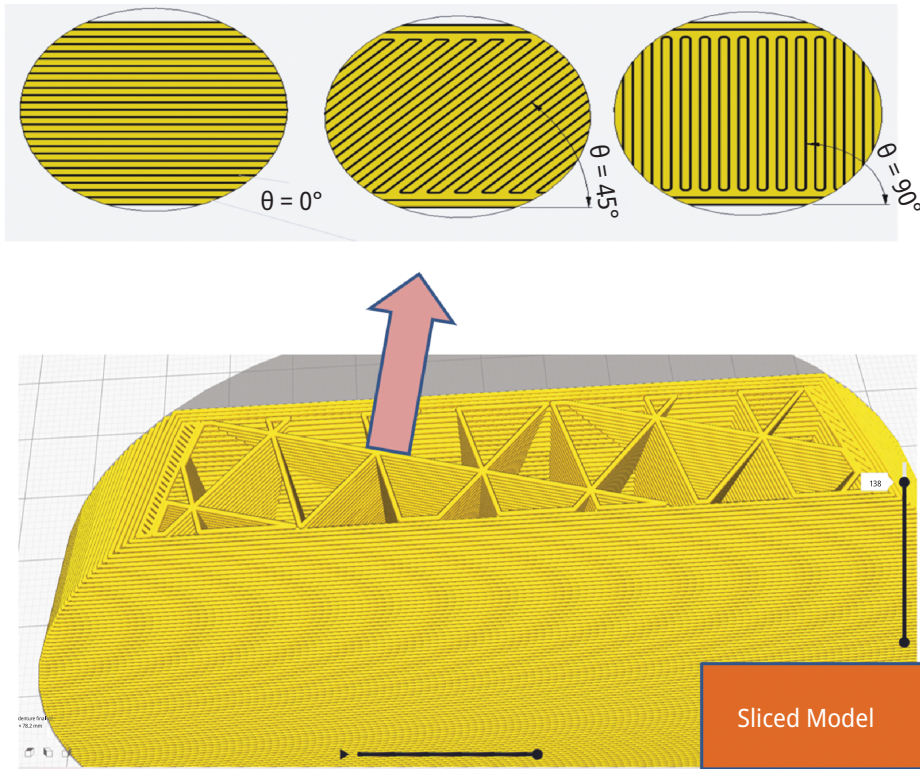


Fig. 13.10: Layer orientation.

The level of accuracy in 3DP is directly related to the density of triangles used to represent the object. Increasing the number of triangles improves accuracy but also extends the printing time. Striking the right balance between accuracy and printing

time is crucial as explained using Fig. 3.10. Print speed is another critical factor influencing the quality and accuracy of the final product. Higher speeds may introduce vibrations and inertia that compromise accuracy, while slower speeds generally yield better results. Determining the optimal speed for a specific object and printer is necessary to achieve the desired level of accuracy. The chosen layer pattern during printing also impacts the strength and structural integrity of the printed object. Different layer patterns, such as rectilinear or honeycomb, offer varying levels of support and affect the overall quality of the final product. Slicing software, such as Cura Ultimaker, is used to configure these parameters. It allows users to adjust settings such as layer height, infill density, print speed, and layer pattern. By selecting appropriate values for these parameters, users can achieve the desired level of accuracy in their prints. However, it is important to note that the accuracy of the final product can still vary depending on the chosen software and its settings. In conclusion, software plays a critical role in 3DP accuracy. Slicing errors, the staircase effect, triangle density, print speed, and layer pattern all influence the accuracy and quality of the printed object. By using reliable slicing software, configuring the parameters correctly, and understanding the software's capabilities, users can optimize accuracy in their 3DP projects.

13.9 Conclusion

This study provides an exhaustive and in-depth analysis of the development and design of 3DP techniques. It includes conventional and unconventional methods, recent advancements in printing technologies, and the revolutionary effects of 3DP on industries. The study highlights the significance of precision and miniaturization in micro and nanoscale 3DP, permitting the fabrication of intricate and accurate structures with applications in fields such as microelectronics, microoptics, LOC devices, and nanomedicine. It also examines current trends and prospective directions in 3DP, focusing on concepts such as mass customization, production on demand, and distributed manufacturing, which have the potential to transform supply chains and business models. In addition, the study introduces the concept of 4DP, which combines the dimension of time with intelligent materials to produce dynamically changing and adaptable objects with applications spanning from biomedical engineering to responsive architecture. The study also examines the significance of printing file formats and software in guaranteeing compatibility, precision, and postprocessing refinement. This exhaustive examination of 3DP techniques provides researchers, practitioners, and industry professionals with valuable insights for navigating the dynamic landscape of 3DP and making well-informed decisions within their respective disciplines.

13.10 Future prospects

Continued research and development in the 3DP field constitutes the future scope of this endeavor. Further advancements in materials, printing technologies, and software are anticipated as the technology continues to evolve. These advancements will facilitate the creation of more complex and functional structures, thereby expanding the applications for 3DP. To expand the potential applications in industries such as aerospace, healthcare, and automotive, research can concentrate on developing new materials with improved properties, such as enhanced strength, flexibility, and biocompatibility. In addition, the exploration of novel printing techniques and methods, such as multimaterial printing, bioprinting, and large-scale AM, can open up new opportunities and improve the printing process's efficacy. In addition, software development will play a significant role in enhancing the design and printing workflow, allowing for greater precision, compatibility, and post-processing automation. Enabling more complex geometries, enhanced color representation, and streamlined post-processing techniques, advancements in file formats and software tools can address current limitations and difficulties. In addition, collaboration between academic institutions, businesses, and government agencies will play a crucial role in promoting the adoption and integration of 3DP technologies across a variety of industries. Continued investment in research and development, in addition to the establishment of standards and regulations, will accelerate the growth and acceptance of 3DP. The future of 3DP contains enormous potential for innovation, disruption, and transformation in manufacturing, healthcare, architecture, and other industries. Exploration, technological progress, and collaboration will shape the future of 3DP and unlock its maximum potential.

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14 Additive manufacturing and 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

Abstract: For the Industry 4.0-enabled digital biomedical and pharmaceutical sectors, additive manufacturing (AM) and four-dimensional (4D) printing have emerged as viable technologies. Layer-by-layer printing of 3D structures is what is known as AM, whereas 4D printing goes one step further by enabling the printed structures to change shape or functionality over time in response to outside stimuli. In the biomedical sector, AM and 4D printing offer the potential to revolutionize medical devices, prosthetics, and implants. In the pharmaceutical sector, AM and 4D printing offer the potential to revolutionize drug delivery systems. In this chapter, we study enabling technologies of drug-delivery systems that can release drugs at specific times and locations in response to physiological cues. This can improve drug efficacy and reduce side effects. However, the implementation of AM and 4D printing in the biomedical and pharmaceutical sectors also presents challenges related to regulatory approval, scalability, and safety. We also discuss AM and 4D printing in this chapter, which have enormous potential for the digital biomedical and pharmaceutical industries. These technologies have the potential to alter the way healthcare is delivered while also improving patient outcomes, lowering healthcare costs, and overcoming implementation-related obstacles.

Keywords: 4D printing, additive manufacturing, Industry 4.0, digital biomedical, pharmaceutical sectors

14.1 Introduction

Known as additive manufacturing (AM), three-dimensional (3D) printing (3DP) is a process for creating 3D objects out of layers of materials such as ceramics, metals, and polymers. It has gained popularity across a wide range of industries, including

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the biomedical and pharmaceutical sectors, because to its ability to build complicated and customized structures with high precision. Recently, a new type of AM called 4D printing has emerged. Making items that change over time in response to environmental factors like heat, light, or moisture is possible using 4D printing. This technology has potential uses in several industries, such as drug delivery and biomedicine. Customized medical implants and prostheses can be made using AM in the biomedical field, enabling a more exact fit and quicker healing. Additionally, it can be required to create complex tissue scaffolds that support the growth of new tissues and organs. The use of 3DP in the pharmaceutical sector to produce specialized drug formulations with exact release patterns enables personalized therapy. Moreover, it can be used to build test versions of medication delivery systems, such as transdermal patches or inhalers, to evaluate their performance and improve their design. By producing things that can alter shape or release medications in reaction to certain stimuli, 4D printing has the potential to revolutionize drug delivery systems. For instance, a 4D-printed tablet might adapt to stomach acidity and change shape, allowing for targeted medicine administration to particular regions of the digestive tract.

14.2 Literature review

Ashima [1] looked into the need for Industry 4.0 technologies for AM processes and looked at the benefits of using IT in AM. Internet of things (IoT) applications in AM increase production process effectiveness, which leads to less manufacturing waste and meets client requirements. AM has become a crucial industrial technique for the development of new products, so it is vital to implement changes to make this technology more user-friendly. González-Henríquez et al. [2] reviewed the fundamental ideas of the most pertinent polymer AM technologies while taking into account the printing technique and benefits and drawbacks. The specific characteristics, traits, and restrictions of the polymer systems now used in the various AM technology fields are described and examined. The process of 4D printing, which produces 3D-printed structures with the capacity to change over time, is then explained. Kantaros et al. [3] discussed Industry 4.0, 3D, and 4D printing, which is used to make customized objects, improve supply chain effectiveness, and reduce costs and lead times. Aerospace, regenerative medical and dental, and automotive industries are among those adopting 3D and 4D printing to create intricate geometries and parts that would be difficult or impossible to create using conventional manufacturing techniques. Horst et al. [4] reviewed a basic understanding of 3DP technology's role in Industry 4.0. 3DP technology are driving the next major industrial revolution. Due to its versatility, AM is key to Industry 4.0 since it reduces complexity, speeds up prototyping, and allows for highly decentralized production processes while also saving time and money. Haleem et al. [5] explored several properties of 4D printing for boosting the industrial area, its development, and applications.

Innovative reversible 4D printing uses precise reversal material during the shapeshift. Mitchell et al. [6] reviewed the present 3DP materials that support the introduction of 4D printing. In various fields, including deployable structures, antennas, and medical supplies, the future looks to potential space applications. Zafar and Zhao [7] used contemporary experimental and theoretical literature to explore the elements of 4D technology, such as conventional methodologies, computational difficulties, reversibility, and present status of 4D printing. The reputation and advancement of 4D printing technology, including the materials, methods, and future uses, were studied by Subeshan et al. [8]. It concludes that there are numerous possible uses for 4D printing technology. The combination of AI and AM to promote the design of intelligent systems was described by Milazzo and Libonati [9], with successful applications in the robotics and bioengineering industries, among others. Mehrpouya et al. [10] looked into the sustainability facets of the AM process and the extra benefits in the sections on the economy, society, and environment. The authors also explored the possibility for future AM research to generate fresh ideas by examining the technology, applications, and material trends of AM. Before, during, and after the COVID-19 epidemic, Rehman et al. [11] explored the promise of AM technologies for biomedical applications along with its relationship to the Industry 4.0 (I4.0) concept. With a stronger emphasis on the comparative analysis of used energy to identify which method is more sustainable, various parameters affecting the sustainable performance in AM for biomedical applications are examined. The successful application of I4.0 to tackle any potential pandemic scenario benefits from current developments in the sector, such as 4D printing and 5D printing. The technique of 4D printing was examined in [12], with a focus on its industrial uses and materials, which offer the significant potential for tissue and organ regeneration as well as existing and future applications. Butt [14] addressed the connections between Industry 4.0 components and AM. The content-centric literature review has examined the need for and advantages of such interconnection. The creation of such a digital thread for AM will have substantial advantages, enable businesses to respond to customer needs more quickly, and hasten the transition to smart manufacturing.

14.3 Overview of Industry 4.0-enabled digital biomedical and pharmaceutical sectors

The phrase “Industry 4.0” refers to the fourth industrial revolution, which is characterized by the use of cutting-edge technologies, such as automation, artificial intelligence, and the IoT, to manufacturing procedures. These processes can be connected and digitalized to create smart factories that are more productive, flexible, and efficient. In the biomedical and pharmaceutical sectors, Industry 4.0 has enabled the development of digital technologies that have transformed the way research, development, and production of drugs and medical devices are carried out [16]. These digital technologies have enabled

more precise and personalized treatments for patients and streamlined manufacturing processes, reducing costs and improving the speed of drug development. One key area of digital transformation in the biomedical and pharmaceutical sectors is the use of big data analytics. The vast amount of data generated from clinical trials, electronic health records, and medical imaging can be analyzed using machine learning algorithms to identify patterns and insights that can inform drug development and personalized medicine. The application of advanced robotics and automation in manufacturing processes is another area of digital revolution. Automated systems can complete repetitive jobs more quickly and accurately, which lowers errors and boosts the effectiveness of production operations. Faster medication development and increased production capacity may result from this. The manufacturing processes of the biomedical and pharmaceutical industries are being transformed by the incorporation of 3D printing and 4D printing. As was already established, these technologies allow for the highly accurate and precise development of customized implants, prosthetics, and drug delivery systems.

14.4 Features of Industry 4.0-enabled digital biomedical and pharmaceutical sectors

A fully automated and networked production system is what the fourth industrial revolution, sometimes known as “Industry 4.0,” aims to create. Due to the adoption of Industry 4.0 technology, the biomedical and pharmaceutical sectors have undergone numerous changes, including (Fig. 14.1):

- *Predictive analytics*: The pharmaceutical business can forecast therapeutic efficacy, safety, and market demand with the aid of sophisticated analytics and AI systems.
- *Advanced manufacturing*: Examples of Industry 4.0 technologies that can improve the effectiveness and precision of medication manufacture while lowering costs include 3DP, robots, and automation.
- *Personalized medicine*: The biomedical industry can develop personalized medicine with the use of Industry 4.0 technology based on the patient’s genetic information, lifestyle, and environmental factors.
- *Smart medical devices*: Industry 4.0 technologies have made it possible to create these devices, which can monitor and analyze patient data in real-time to offer better options for diagnosis and treatment.
- *Blockchain*: Implementing blockchain technology can improve transparency, supply chain management, and medication safety.
- *Cloud computing*: Cloud computing and other Industry 4.0 technologies can assist the biomedical industry in storing and analyzing enormous volumes of data, facilitating improved research and development.

- *Virtual reality*: The use of virtual reality can help to improve medical training, patient education, and the development of new medical devices.

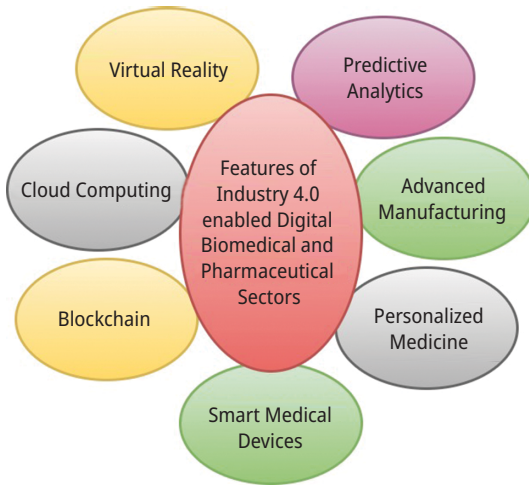


Fig. 14.1: Features of Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

14.5 AM applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

3DP, commonly referred to as AM, is a fundamental innovation that has revolutionized the pharmaceutical and biomedical industries. Industry 4.0 has enabled the integration of 3DP into digital workflows, enabling greater precision, speed, and customization in the development and production of medical devices and drugs. Here are some specific applications of AM for Industry 4.0-enabled digital biomedical and pharmaceutical sectors (Fig. 14.2):

- *Customized medical devices*: AM enables the creation of customized medical devices, such as prosthetics and implants, with greater precision and accuracy. This can lead to faster healing times, reduced risk of complications, and improved patient outcomes.
- *Tissue engineering*: Complex tissue scaffolds that support the development of new tissues and organs can be made via 3DP. This innovation could revolutionize regenerative medicine by enabling the development of patient-specific implants and treatments.
- *Drug delivery systems*: 3DP can be used to create drug delivery systems, such as inhalers and transdermal patches, with customized shapes and release profiles.

This enables more precise and targeted drug delivery, improving the effectiveness of treatments and reducing side effects.

- *Prototyping*: Rapid prototyping of medical equipment and drug delivery systems is made possible by AM, which cuts the time and expense involved with conventional production techniques. This may hasten the creation and commercialization of new goods, enabling businesses to release cutting-edge therapies more quickly.
- *Manufacturing automation*: The integration of AM with automated manufacturing systems can streamline production processes, reducing the need for manual labor and improving efficiency. This can lead to faster production times, reduced costs, and increased production capacity.

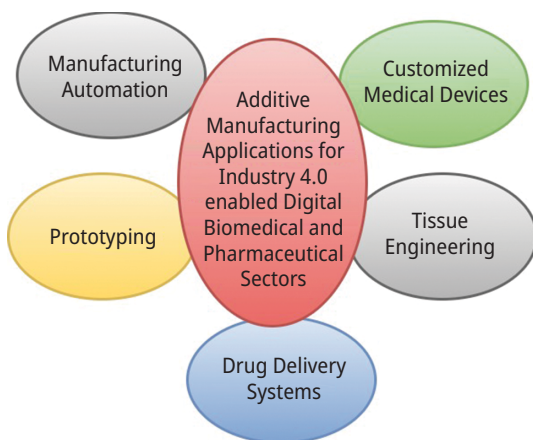


Fig. 14.2: Additive manufacturing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

14.6 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

A relatively new technique called 4D printing, a form of AM, has the power to completely alter the biomedical and pharmaceutical industries. By integrating 4D printing into digital processes, Industry 4.0 has made it possible to create items that may alter over time in response to environmental factors like heat, light, or moisture. Here are some specific uses of 4D printing for the digital biomedical and pharmaceutical industries that are supported by Industry 4.0 (Fig. 14.3):

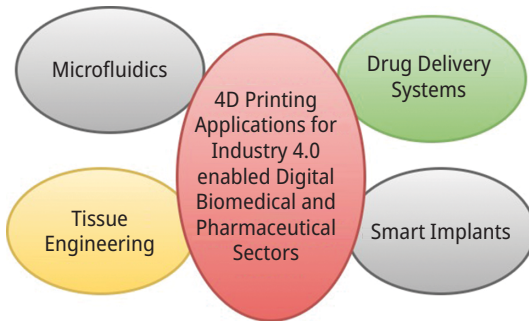


Fig. 14.3: 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

- *Drug delivery systems:* Drug delivery devices that can alter their shape or release medication in response to certain inputs can be made using 4D printing. For instance, a 4D-printed tablet might adapt to changes in stomach pH to deliver drugs to particular regions of the digestive tract. This technology offers the potential to lessen side effects while increasing the efficacy of medication treatments.
- *Smart implants:* Smart implants that may alter their form or operation over time in response to alterations in the body can be produced via 4D printing. For instance, a 4D-printed implant could adapt to changes in bone density to better fit the patient and lower the chance of problems.
- *Tissue engineering:* Complex tissue scaffolds that can assist the development of new tissues and organs can be made via 4D printing. These scaffolds can be made to adapt over time to changes in the environment, changing their shape or function to better assist the growth of the tissues they support.
- *Microfluidics:* Complex microfluidic devices for drug screening and diagnostic uses can be produced using 4D printing. With the ability to adapt over time in response to changes in fluid flow, these devices can be used to create extremely accurate and individualized diagnostic and drug screening instruments.

14.7 Characteristics of AM for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

AM is an innovative technologies that has the potential to transform the biomedical and pharmaceutical sectors in the context of Industry 4.0. Here are some key characteristics of and their applications in these sectors (Fig. 14.4):

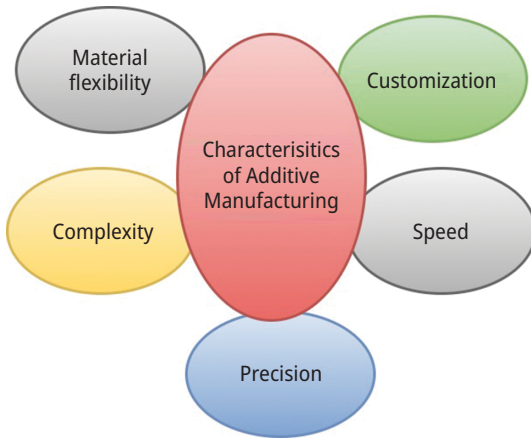


Fig. 14.4: Characteristics of additive manufacturing for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

- *Customization:* AM enables the creation of highly customized medical devices and drug delivery systems, improving patient outcomes.
- *Speed:* Rapid prototyping and production can accelerate the development and commercialization of new products.
- *Precision:* The construction of medical equipment and medication delivery systems can be done with more precision and accuracy thanks to AM, which lowers the risk of complications.
- *Complexity:* With AM, complex geometries and structures that are difficult to manufacture using traditional manufacturing techniques can be produced.
- *Material flexibility:* Metals, polymers, and ceramics are just a few of the materials that can be used in AM to create extremely effective and biocompatible medical devices and drug delivery systems.

14.8 Characteristics of 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

In the context of Industry 4.0, one of the cutting-edge technologies that has the potential to revolutionize the biomedical and pharmaceutical industries is 4D printing. Here are some key characteristics and their applications in these sectors (Fig. 14.5):

- *Dynamic functionality:* The effectiveness of medical devices and drug delivery systems is enhanced by the use of 4D printing to create items that can alter over time in response to external stimuli in terms of shape, size, or function.

- *Responsive design:* By using 4D printing, it is possible to create items that can adapt to changes in their environment, such as variations in temperature, light, or humidity, enhancing their usefulness and functionality.
- *Material selection:* Shape-memory polymers, hydrogels, and composite materials can all be used in 4D printing to create highly functional and biocompatible medical devices and drug delivery systems.
- *Precision:* The creation of medical devices and drug delivery systems may be done more precisely and accurately thanks to 4D printing, lowering the chance of complications.
- *Automation:* The integration of automated production systems with 4D printing can decrease the demand for manual labor and increase productivity.

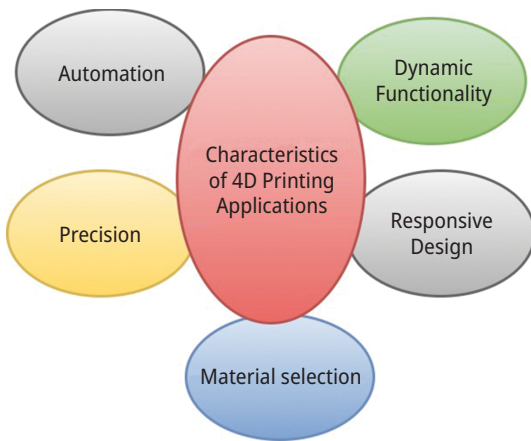


Fig. 14.5: Characteristics of 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

14.9 Advantages of AM for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

AM has several advantages for the biomedical and pharmaceutical sectors in the context of Industry 4.0. Here are some of the main advantages (Fig. 14.6):

- *Customization:* AM enables the creation of highly customized medical devices and drug delivery systems that can be tailored to individual patients' needs, improving patient outcomes.
- *Speed:* AM can accelerate the development and production of medical devices and drug delivery systems, reducing time-to-market and improving patient access to new treatments.

- *Cost-effectiveness*: AM can reduce costs associated with traditional manufacturing methods, including tooling and labor costs.
- *Waste reduction*: AM can reduce waste by minimizing material usage and creating products with highly optimized geometries.
- *Design freedom*: More design flexibility and creativity are made feasible by the use of AM, which makes it possible to manufacture extremely complex geometries and structures that are either impractical or impossible to do so using traditional production techniques.

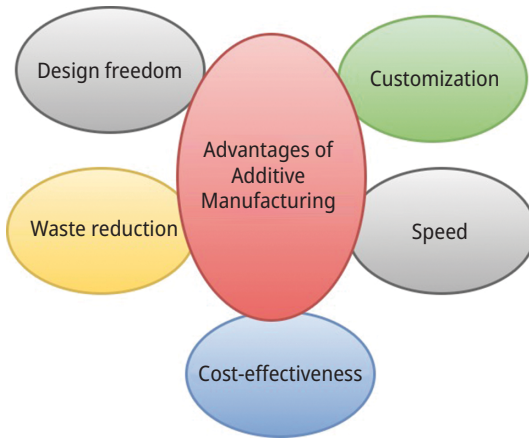


Fig. 14.6: Advantages of additive manufacturing for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

14.10 Advantages of 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

4D printing has several advantages for the biomedical and pharmaceutical sectors in the context of Industry 4.0. Here are some of the main advantages (Fig. 14.7):

- *Dynamic functionality*: The effectiveness of medical devices and drug delivery systems is enhanced by the use of 4D printing to create items that can alter over time in response to external stimuli in terms of shape, size, or function.
- *Responsive design*: By using 4D printing, it is possible to create items that can adapt to changes in their environment, increasing their usefulness and efficacy.
- *Reduced assembly requirements*: 4D printing can create objects that are fully or partially self-assembling, reducing the need for manual assembly and improving efficiency.

- *Precision:* 4D printing can create highly precise and accurate structures, reducing the risk of complications and improving patient outcomes.
- *Material selection:* High-functioning and biocompatible medical devices and drug delivery systems can be produced via 4D printing using a variety of materials, including biocompatible and biodegradable ones.

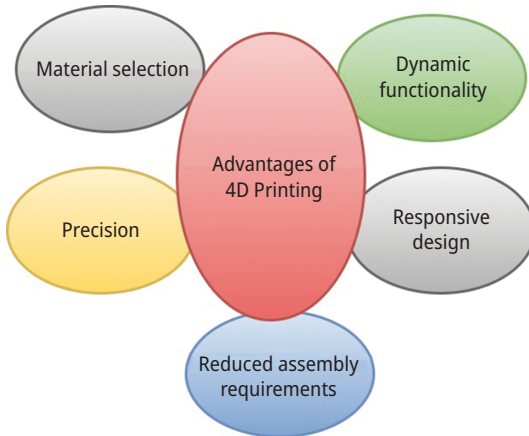


Fig. 14.7: Advantages of 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

14.11 Disadvantages of AM for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

While AM has many advantages for the biomedical and pharmaceutical sectors in the context of Industry 4.0, there are also some disadvantages to consider. Here are some of the main disadvantages (Fig. 14.8):

- *Material limitations:* While AM can use a wide range of materials, some materials may not be suitable for certain applications, or may be prohibitively expensive.
- *Surface finish:* The surface finish of parts created through AM may not be as smooth or polished as those created using traditional manufacturing methods, which can impact functionality and aesthetics.
- *Size limitations:* Some AM processes may have limitations on the size of parts that can be created, which can limit their applications in certain sectors.
- *Regulatory challenges:* As AM is a relatively new technology, regulatory approval processes may be uncertain or time-consuming, which can impact commercialization and adoption.

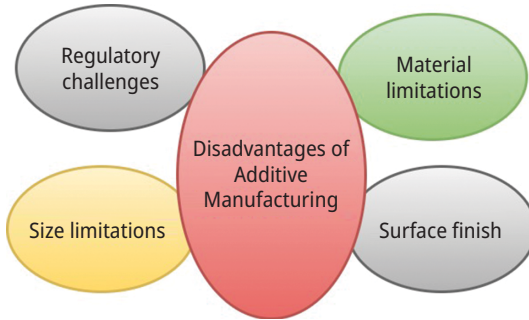


Fig. 14.8: Disadvantages of additive manufacturing for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

14.12 Disadvantages of 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

4D printing has many advantages for the bio-medical and pharmaceutical sectors in the context of Industry 4.0, there are also some disadvantages to consider. Here are some of the main disadvantages (Fig. 14.9):

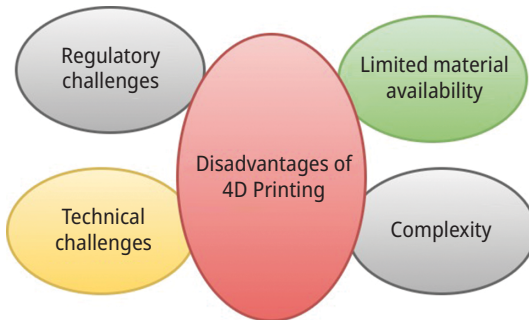


Fig. 14.9: Disadvantages of 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

- *Limited material availability:* Some 4D printing materials may be more expensive or difficult to source compared to traditional materials.
- *Complexity:* 4D printing can be more complex than traditional manufacturing methods, which can impact design and production processes.

- *Technical challenges:* 4D printing requires specialized technical expertise, which may be a challenge for some organizations to acquire or retain.
- *Regulatory challenges:* As with AM, regulatory approval processes for 4D printing may be uncertain or time-consuming.

14.13 Challenges of AM for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

AM has several challenges that need to be addressed for their successful adoption in the biomedical and pharmaceutical sectors in the context of Industry 4.0. Here are some of the main challenges (Fig. 14.10):

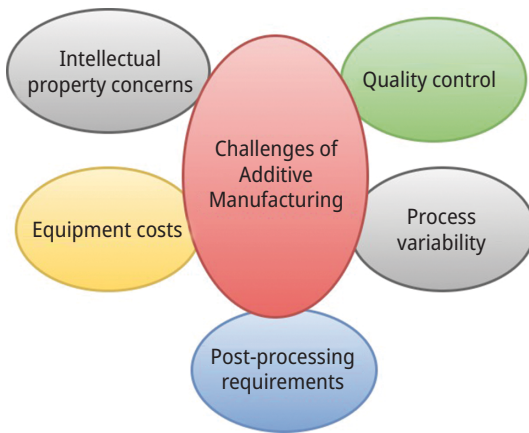


Fig. 14.10: Challenges of additive manufacturing for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

- *Quality control:* AM processes can be more difficult to control and validate compared to traditional manufacturing methods, which can impact quality and safety.
- *Process variability:* AM processes can be more variable than traditional manufacturing methods, which can impact consistency and repeatability.
- *Post-processing requirements:* Parts created through AM may require additional post-processing steps, which can impact production time and costs.
- *Equipment costs:* AM equipment can be expensive, which can impact the cost-effectiveness of these processes.
- *Intellectual property concerns:* AM can enable the creation of highly complex and customized parts, which can raise concerns about intellectual property and counterfeiting.

14.14 Challenges of 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors

4D printing has several challenges that need to be addressed for their successful adoption in the biomedical and pharmaceutical sectors in the context of Industry 4.0. Here are some of the main challenges (Fig. 14.11):

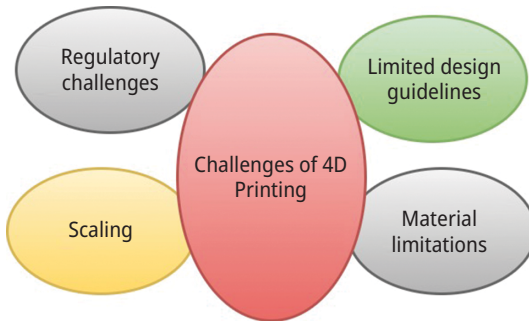


Fig. 14.11: Challenges of 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

- *Limited design guidelines:* There are currently limited guidelines for designing 4D printed objects, which can impact the development and production of these objects.
- *Material limitations:* Some 4D printing materials may not be suitable for certain applications, which can impact functionality and effectiveness.
- *Scaling:* Scaling 4D printing processes can be challenging due to the complex nature of these processes and the need for specialized expertise.
- *Regulatory challenges:* As with AM, regulatory approval processes for 4D printing may be uncertain or time-consuming.

14.15 Case study

The development, manufacturing, and distribution of biomedical and pharmaceutical products could significantly be revolutionized by the rapidly developing technologies of AM and 4D printing. In this case study, we will explore the applications of AM and 4D printing in the digital biomedical and pharmaceutical sectors.

- *AM in the digital biomedical sector:* Additive manufacturing has already been used extensively in the development of medical implants, prosthetics, and orthotics. The ability to create complex geometries and shapes that were previously im-

possible with traditional manufacturing techniques has led to the creation of customized implants and prosthetics that fit patients perfectly. This has reduced surgery time and improved patient outcomes. Personalized medical equipment including hearing aids, dental implants, and drug delivery systems are also being created using AM. AM can assist manufacturers to minimize their inventory, increase productivity, and cut costs by being able to build one-off products fast and affordably.

- *4D printing in the digital biomedical sector:* In reaction to particular stimuli like temperature, pressure, or moisture, 4D printed objects can change over time in terms of shape or functionality. Biomedical applications of this technology include the development of intelligent implants, drug delivery systems, and tissue engineering scaffolds that can adapt to the needs of the body. In order to encourage bone growth, for instance, researchers at the University of Wollongong have created a 4D-printed implant that can alter shape over time. The implant is constructed of a shape-memory polymer that can change shape in response to body heat and perfectly fit the bone cavity.
- *AM in the digital pharmaceutical sector:* Pharmaceutical items are also being developed via AM. Customized dose forms and drug delivery methods can enhance patient outcomes, lower costs, and boost treatment effectiveness. A complicated structure that can be utilized to test medications in a lab setting, like a microfluidic device, can be created using AM. These gadgets can simulate the human body and offer a more precise illustration of how the medication would behave in real life.
- *4D printing in the digital pharmaceutical sector:* The development of drug delivery systems using 4D printing has a lot of potential. By creating materials that respond to specific stimuli, it is possible to create drug delivery systems that can release pharmaceuticals over a predetermined period of time or in reaction to specific environmental conditions. A 4D printed pill, for instance, that delivers drugs over a specified period of time was developed by researchers at the Massachusetts Institute of Technology. The hydrogel used to make the tablet expands in the stomach and releases the medication over time. As a result, fewer dosages are required, and patient compliance is enhanced. The digital biomedical and pharmaceutical sectors provide tremendous promise for AM and 4D printing. With the use of these technologies, patients' outcomes can be improved while costs are decreased and medicine efficacy is increased. Customized implants, prosthesis, drug delivery systems, and dosage forms can also be created. It is possible that we will see even more creative uses of AM and 4D printing in these fields as technology develops.

14.16 Research methodology to AM and 4D printing applications

Integrating 4D printing and AM applications for Industrial 4.0, the digital biomedical and pharmaceutical industries need a thorough research process that covers several stages. The following is a potential research methodology that can be used (Fig. 14.12):

- *Literature review:* Conduct a comprehensive literature review to identify existing knowledge, concepts, theories, and practices related to AM and 4D printing applications, Industry 4.0, digital biomedical, and pharmaceutical sectors.
- *Research questions:* Develop research questions that aim to explore the challenges and opportunities of implementing additive manufacturing and 4D printing applications in the Industry 4.0-enabled digital biomedical and pharmaceutical sectors.
- *Research design:* Opt for a methodology that addresses the research questions. Because it enables the collection and analysis of both qualitative and quantitative data, a mixed-methods approach is advised. The design should take the research's ethical considerations into account.
- *Data collection:* Gather information from a variety of sources, such as surveys, observations, and interviews. A wide range of stakeholders, such as researchers, clinicians, and business professionals, should provide data.
- *Data analysis:* Perform a statistical and qualitative analysis of the data. In order to adopt AM and 4D printing applications in the Industry 4.0-enabled digital biomedical and pharmaceutical sectors, data analysis should identify the major problems and opportunities.
- *Findings and recommendations:* Summarize the research findings and offer suggestions for the implementation of 4D printing and AM applications in the Industry 4.0-enabled digital biomedical and pharmaceutical industries. The research findings should serve as the foundation for recommendations that also consider the implementation's potential ethical, legal, and social ramifications.
- *Dissemination and validation:* Presenting the results and suggestions to the appropriate parties, such as researchers, doctors, and business professionals, will serve to validate them. Publicize the results and suggestions in publications, speeches, and conferences.

14.17 Comparative analysis

By contrasting the advantages, difficulties, and potential effects of the two technologies in the context of the relevant sectors, it is possible to conduct a comparative analysis of implementing AM and 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors. A possible structure for carrying out such a comparison analysis is as follows:

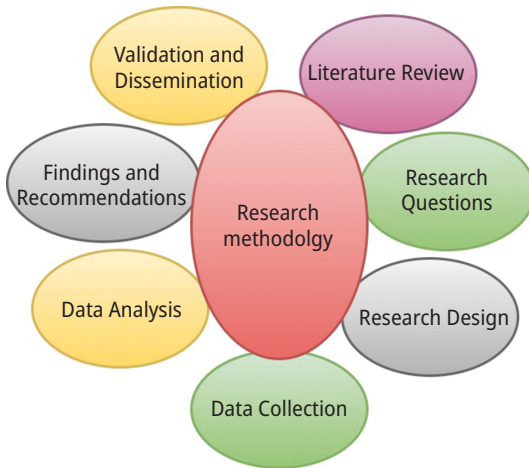


Fig. 14.12: Research methodology to additive manufacturing and 4D printing applications.

– **Benefits:**

Additive manufacturing: Complex geometries and customized parts can be created via AM, allowing for the creation of patient-specific implants, prosthetics, and medical equipment. It also reduces waste and energy consumption, and can accelerate the production process [17].

4D printing: 4D printing builds on AM by enabling the fabrication of dynamic and responsive structures that can change their shape, size, and properties over time or in response to environmental stimuli. This can lead to the development of self-assembling, self-repairing, and adaptive devices [18].

– **Challenges:**

AM: The creation of biocompatible and sterilizable materials, as well as the validation and certification of the printed parts, are necessary for the application of additive manufacturing in the biomedical and pharmaceutical sectors. Moreover, digital design, simulation, and quality control technologies must be integrated [19].

4D printing: Several technological and scientific issues still need to be resolved in order to advance 4D printing, including the improvement of the printing procedure, the creation of new materials, and the management of the shape-changing mechanisms. Moreover, new design and simulation tools must be created [20].

– **Potential impact:**

AM: AM has the potential to transform the biomedical and pharmaceutical sectors by enabling the production of patient-specific and personalized devices, reducing costs and time-to-market, and increasing innovation and creativity.

4D printing: 4D printing has the potential to create entirely new classes of devices and systems that can adapt to changing conditions, repair themselves, or interact with the human body in novel ways. It also has the potential to reduce the need for multiple devices and interventions, and to improve patient outcomes and quality of life.

Table 14.1 depicts the comparative analysis of different techniques in AM and 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

Tab. 14.1: Comparative analysis of different techniques in additive manufacturing and 4D printing applications for Industry 4.0-enabled digital biomedical and pharmaceutical sectors.

References	Additive manufacturing	4D printing applications	Industry 4.0	Digital biomedical	Pharmaceutical
[1]	✓	✓	✓	×	×
[2]	✓	✓	×	✓	×
[3]	✓	✓	✓	×	×
[4]	✓	×	✓	×	×
[5]	✓	✓	×	×	×
[6]	✓	✓	×	×	×
[7]	✓	✓	×	×	×
[8]	×	✓	×	×	×
[9]	✓	×	×	×	×
[10]	✓	×	✓	×	×
[11]	✓	×	×	✓	×
[12]	✓	✓	×	×	×
[13]	✓	✓	×	✓	×
[14]	✓	×	✓	×	×
[15]	✓	✓	×	×	×
Proposed methodology	✓	✓	✓	✓	✓

14.18 Future perspectives of AM and 4D printing applications

Given that these technologies are developing and getting more sophisticated, the future of AM and 4D printing in the digital biomedical and pharmaceutical industries looks promising. Here are some perspectives on the future of AM and 4D printing in these sectors (Fig. 14.13):

- *Increased customization and personalization:* The capacity of AM and 4D printing to create individualized and customized products is one of their key benefits. As the technology becomes more advanced and cost-effective, we can expect to see

more personalized medical devices, implants, and drug delivery systems being produced. This will improve patient outcomes and reduce healthcare costs.

- *Enhanced functionality:* The biomedical and pharmaceutical industries stand to gain significantly from the capability of 4D printing to create materials that change shape or function over time in response to particular stimuli. We can expect to see more smart implants and drug delivery systems being developed that can respond to the body's changing needs.
- *Improved efficiency:* By cutting manufacturing time, eliminating waste, and enhancing quality control, AM and 4D printing can contribute to enhancing the efficiency of the biomedical and pharmaceutical industries. Manufacturers will be able to make goods more quickly, more affordably, and with a higher level of general quality as a result.
- *Greater collaboration:* As AM and 4D printing technologies advance, we may anticipate more cooperation between academics, manufacturers, and healthcare practitioners. This will hasten the development and uptake of new technologies, improving patient outcomes and the quality of the healthcare system as a whole.
- *Emergence of new applications:* We may anticipate the emergence of new AM and 4D printing applications in the biological and pharmaceutical industries as the technology advances. For instance, researchers are investigating the use of AM to create artificial organs, and 4D printing may be utilized to create drug delivery systems that are stimuli-responsive.

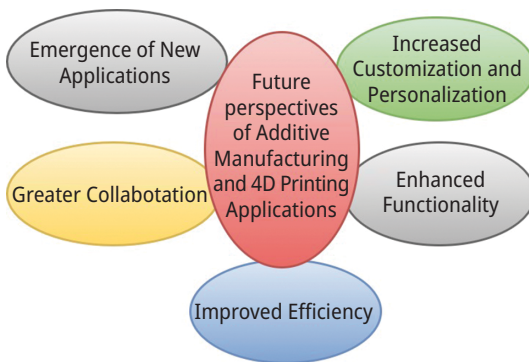


Fig. 14.13: Future perspectives.

14.19 Conclusion

Both AM and 4D printing are disruptive technologies with the potential to completely change the pharmaceutical and digital biomedical industries. Compared to conventional production methods, these technologies have various benefits, such as better

customization, higher functionality, increased efficiency, and increased collaboration. In the field of digital biomedicine, individualized implants, prosthetics, and orthotics have already been created using AM, while smart implants, drug delivery systems, and tissue engineering scaffolds are being created using 4D printing. In the field of digital pharmaceuticals, AM is used to create customized dosage forms and stimuli-responsive drug delivery systems, while 4D printing is employed to create personalized drug delivery systems. We can anticipate even more cutting-edge applications of AM and 4D printing in the digital biomedical and pharmaceutical industries as technology advances, such as the creation of artificial organs and the use of AM to create complex structures like microfluidic devices for drug testing.

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15 Application of three-dimensional printing in medical, agriculture, engineering, and other sectors

Abstract: Three-dimensional (3D) printing, also known as additive manufacturing, has been applied in various applications. Nowadays, traditional manufacturing processes are becoming obsolete with the evolution of 3D printing. This technology offers a completely new paradigm for modern-day manufacturing practices and carries significant scientific, economic, environmental, and political implications. Currently, 3D printing is gaining increasing attention from various industries due to its revolutionary effects in manufacturing, medicine, agriculture, and other sectors. Consequently, efforts are underway to improve the efficiency and scale of 3D printing processes. In this paper, we will provide a brief overview of different applications of 3D printing in various sectors.

Keywords: Three-dimensional printing, environmental, medical, agriculture, economic

15.1 Introduction

15.1.1 The three-dimensional printing

By adding additional material in sequential steps, three-dimensional (3D) printing can be used to create physical objects from geometric representations [1]. Transformative technology has a long history. The terms atomic energy, light bulb, steam engine, and microchip, to name a few, forever changed the globe. Since their potential impact must have been virtually unimaginable at the beginning of the method, it frequently takes decades for these innovations to change the way we carry out our daily activities. And it is quite unlikely that Tim Berners-Lee, who founded the World Wide Web 20 years ago, could have predicted the impact it would have on our global “operating system” even in his wildest dreams. Another cutting-edge technology that holds the

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potential to transform the world is currently gaining popularity. 3D printing (3DP) that was also termed to be as additive manufacturing (AM), is an innovative new technology which may hold the potential to fundamentally alter how manufacturing as well as design have been performed for the past two centuries. Additive manufacturing (AM) also has significant implications for social, geopolitical, demographic, economic, and environmental factors. A landing gear might be cut out of a block of titanium using “subtractive” manufacture, which involves extracting material from a larger piece of material, as opposed to additive manufacturing, which builds goods layer by layer. The seemingly little differential of adding as opposed to removing has major implications [2]. Since the decades-old technology has finally begun to perform well enough to be directly formed into end-use devices, 3DP, which was also termed as additive manufacturing, has attracted the attention of the general public and the media. Standard 3DP processes that are very common today include the material extrusion, the vat photopolymerization, the sheet lamination, the powder bed fusion, the material jetting, the binder jetting, as well as the directed deposition of energy. Each of these methods builds parts layer by layer as well as provides a lot of options for price, materials, and feature detail. Whereas the traditional manufacturing technologies, like that of forging, casting, injection, molding and machining were well fitted for the mass productivity of an identical commodity items, 3DP offers for the production of an complex geometric shapes which must be mass-customized, because there were no die as well as mold is needed as well as design concepts were been translated into the products by the help of direct digital manufacturing. As a result, the additively layered technique allows for the combinations of several components into a single unit, which minimizes the need for additional assembly steps. As the original 3DP patents start to lapse, an increasing number of low-cost desktop systems are becoming available. These systems may increase accessibility for society as a whole. Industries are investing in production systems to create complicated components for customized vehicle bodies, jet engines, and pharmaceuticals now that they are aware of the benefits of manufacturing these technologies. Although recent advancements in standard 3DP technologies have made it possible to print in a wider variety of materials, containing polymers, metals, and ceramics, as well as the structures that resulted were typically restricted to a single material, or, at best, a small number of the compatible materials [3]. As we are all aware, additive manufacturing has gained popularity across the globe, particularly in the aerospace, healthcare, construction, and biomedical industries. A request for local and government practitioners to promote the development of this new technology for numerous industries – most notably for biomedical products – came forth in Malaysia as a result of the local industries’ poor embrace of this type of technology [4]. The term “three-dimensional printing,” commonly referred to as “additive manufacturing,” describes a group of cutting-edge technologies that have gradually been used to produce 3D objects in a range of fields, including engineering, pharmaceuticals, medicine, and agri-food. Because they offer chemical resistance, are less expensive, and are easy to process, poly-

meric materials are one of the primary materials processed by 3DP techniques like selective laser sintering (SLS) , fused deposition modeling (FDM) , as well as stereolithography (SLA). Therefore, one of the main drawbacks of using these materials exclusively (e.g., PLA (polylactic acid)) in the manufacturing methods is the finished product's poor mechanical and tensile properties. To overcome these limitations, fillers have to be introduced as strengthening agents to the polymeric matrix at the time of manufacturing. These transport both organic and inorganic substances, such as carbon fibers, silicon, glass, metals, or ceramic. Employing natural polymers (proteins and polysaccharides) that have come out from the plants or may be acquired from biomass or industrial/agricultural wastes as reinforcing agents is one emerging strategy in front of us. The advantages of applying these kinds of organic materials as the fillers for 3DP were relatable to their accessibility as well as the potential to produce printed specimens with a low environmental effect as well as a higher biodegradability. They thus offer a “green option” for 3DP technology, as well as various studies examining their abilities in improving the mechanical properties of 3D printed goods were published the year before. The following chapter provides a summary of the literature so far on the use of natural polymers as 3DP reinforcement [5].

15.1.2 Evolution of 3D printing

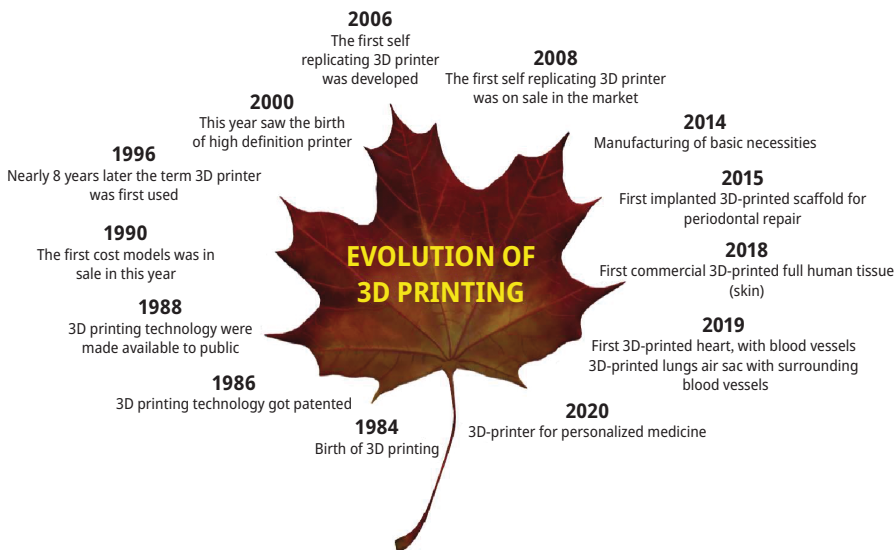


Fig. 15.1: Evolution of 3D printing.

Figure 15.1 represents the evolution of 3DP from 1984 to 2020. Bioprinting was firstly demonstrated in the year 1988 by Klebe by the help of the standard Hewlett-Packard

(HP), an inkjet printer used to put the cells by cyto-writing method [6]. Therefore, in the year 1988, the first SLA 3D printer was available [7]. Scott Crump created the FDM process in the year 1989 [8]. In 1999, it has been reported that the first organ applied for (bladder) transplantation was printed [9]. The first extrusion-based 3D printer (3D Bioplotter) debuted in the year 2000, and the first kidney was manufactured using micro-extrusion 2 years later [10]. Wilson and Boland modified a regular HP inkjet printer to create the first inkjet bioprinter in the year 2003 [11]. At the University of Bath in Somerset, the UK, the RepRap (Replicating Rapid Prototyping) project was established in 2005 with the goal of creating a less expensive 3D printer that would create most of its components [12]. In 2007, the first 3D printer using SLS became available [13]. The first prosthetic limb was printed in 2008 [14], and the first 3D blood vessel was printed in 2009 [15]. The first 3D printed jaw was developed in 2012 [16]. The year 2014 reported the first 3DP of the liver tissue [17] but along with the arrival of the first desktop 3D printer [18]. Beheshtizadeh et al. developed as well as applied the first 3D printed scaffold for the periodontal repair in 2015 [19]. In 2018, the first commercial 3D full human (skin) product [20] was printed as well as in 2019, Noor et al. successfully generated a perfusable heart having decremented dimensions [21]. The year 2020 paved the route for the personalized application of 3DP in the fields of medicine [22]. Particularly in the domains of dentistry and periodontics, 3DP has produced many positive results. 3DP technologies have been applicable to study the treatment of the disease called gingival lesions (the treatment of a gingival recessions, the gingivectomies, or the restoration of a smile designing) and the regeneration of the periodontal tissues (the periodontal ligaments, alveolar bone, as well as cement) [23, 24].

15.1.3 Benefits of 3D printing

It is still believed that 3DP plays a significant role in providing practical and financial benefits to supply chains. The applications of 3DP in the food industry are becoming increasingly flexible and complex, which puts pressure on printing companies. Three-dimensional printed food is projected to help manage food product characteristics, improve food diversity, and reduce waste.

Despite the enormous promise of 3DP in the food industry, the technology is still in its infancy. Therefore, the goal of this research is to identify the various obstacles that could hinder the adoption of 3DP in the food industry. The study examines the connections between implementation constraints for 3D food printing in sustainable food supply chains. The hybrid Interpretive Structural Modeling (ISM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodologies were employed to understand the contextual and hierarchical relationships between the identified barriers.

Experts in food printing identified and validated 13 hurdles. The high cost of consumables was highlighted as a significant obstacle to integrating 3D food printing into

supply chains. In order to advance the production of sustainable 3D food printing-based supply chains, the study also reported on the identified linkage barriers and dependency barriers, and provided suggestions for overcoming some of the implementation hurdles [25].

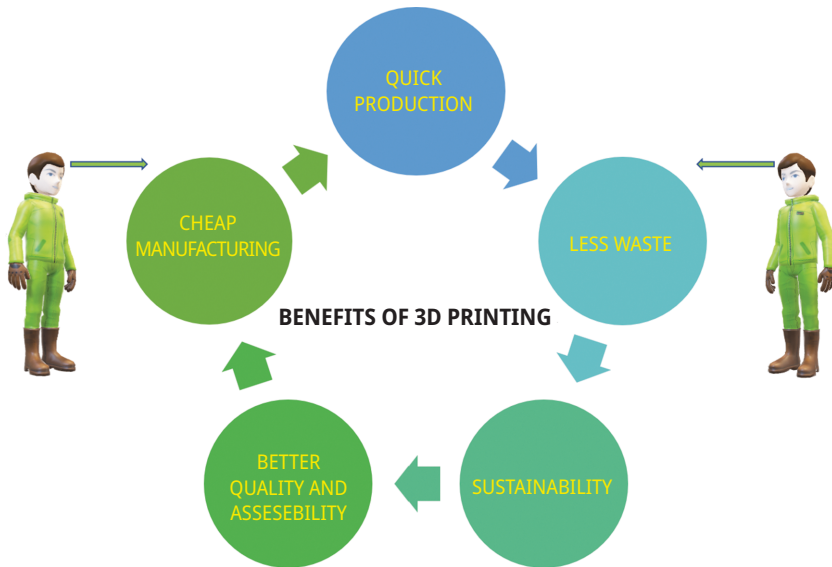


Fig. 15.2: Benefits of three-dimensional printing.

Figure 15.2 represents the different benefits of 3DP such as quick production, better quality and assessment, cheap manufacturing, lesser waste as well as sustainability and many more as discussed below.

a. **Flexibility:** 3DP allows the design and printing of more intricate models than that of conventional manufacturing methods. The traditional methods are dominated by the limitations on a design which does not prefer the application of 3DP.

b. **Competitive advantage:** Due to the lower costs and speed of 3DP, product life cycles were deduced. Businesses may enhance and improve the product allowing them to offer excellent products in a lesser amount of time.

c. **Error reduction:** If it comes to designing products as well as parts, designers need to consider the term efficiencies. A lot of products and parts need a higher number of steps by the help of traditional methods of manufacturing in order to be developed. Hence, each and every step must give rise to an error, with a risk of starting over again that may lead to issues with an overall manufacturing method. A single step of a manufacturing method is much necessary.

d. **Accessibility:** Compared to traditional manufacturing settings, the term “3-dimensional printing systems” was far more widely understood and could be applied by a much wider variety of people. A 3DP setup is far less expensive when compared to the enormous cost associated with setting up traditional manufacturing methods. In addition, 3DP is entirely automated, requiring little to zero extra labor to run, oversee, as well as to maintain the equipment, making it much more accessible than that of conventional production processes.

e. **Sustainability:** Less waste is produced by the production of 3DP and generally is recyclable in nature and equals less environmental impact. The deductive manufacturing processes, such as CNC milling, give rise to huge amounts of waste materials. These methods are able to discard a notable amount of the materials from the first initial block. Therefore, 3DP only uses the materials which were needed to create a part. Hence, the materials must be reused as well as recycled for the further processes. Therefore, additive manufacturing gives rise to very little waste as well as saves a lot of money also.

f. **Rapid prototyping:** 3DP offers the productivity of parts in a matter of hours as well as may increments the prototyping process. This offers each step to be done faster. As compared to the manufacturing prototypes, 3DP is termed to be a cost-effective as well as faster to produce parts as the designing must be done in hours that offer for every designing change to be done at a faster speed.

g. **Production on demand:** The key advantage of 3DP is the abilities to have complete creative freedom. It might also enable designers to alter existing designs. Since 3DP works best for one-off productions and for producing individual parts in a single step, the capability to customize is available to take advantage of it. Due to its potential to provide personalized implants and aids, 3DP has thus been adopted by a number of businesses, including the dental and medical fields. In fact, the sports equipment was made to fit the players as well, which led to the creation of unique, person-specific parts in a way that had never been observed before. The traditional methods required cutting as well as using molds, making customization an extremely time-consuming process. In contrast to this procedure, product customization made possible by 3DP may have increased the products' structural integrity, accomplished sophisticated alterations, and redesigned the parts to meet specific needs. Such customization may open up an infinite number of possibilities for 3DP.

h. **Strong and lightweight parts:** The primary 3DP material which were applied are plastic. Hence, certain metals must also be used for 3DP. Therefore, the plastics were found to be a better choice due to its lesser weight than that of their metal counterparts. This was termed to be crucial in the areas such as automotive and aerospace, where lightweight is a big issue as well as may also offer higher fuel efficiencies.

- i. **Advanced healthcare:** 3DP is much involved in the medical field as a lot of applications are seen in current time and will be delivered much more in the upcoming generations.
- j. **Reduce time:** The fast-paced society we currently live in necessitates that everything be produced rapidly, which is why 3DP is so important. One of the highest advantages of 3DP is that components as well as products can be produced far more quickly than they can with the aid of conventional techniques. In a matter of hours, the complex concepts went from being a CAD model to becoming a reality. This provides design concepts in a way that makes it possible for them to be quickly validated and created in a short amount of time. It is thought to be more advantageous than conventional methods because they require weeks or months to complete the entire production process, starting with the design phase and ending with the prototype phase.

15.1.4 Applications of 3D printing

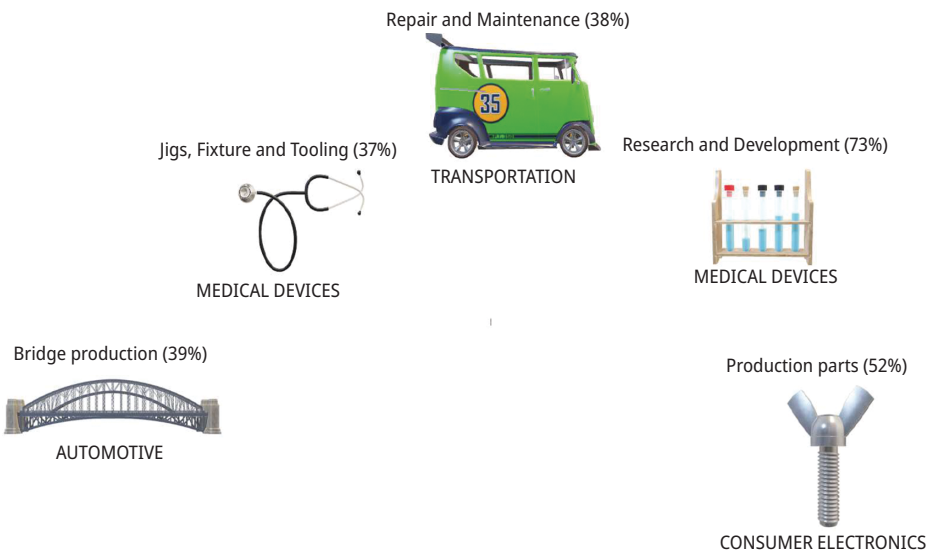


Fig. 15.3: Diagrammatic representation of the most common industry for each 3D printing application besides prototyping.

Figure 15.3 represents the diagrammatic representation of the most common industry for each 3DP application beside the prototyping. It has been discovered that 3DP is developing as an enabling process or technology for a wider range of unique applications. From a theoretical standpoint, the materials that were available, the speed of manufacturing, and the resolution of the 3DP technologies may be taken into account

for each of the unique applications. This chapter provides a very basic grasp of 3DP techniques along with the current research and development of the novel 3DP materials, like composites, ceramic materials, smart materials, and electronic, biomedical, and smart materials. It should be noted that the variety of 3DP systems is what gives 3DP materials their versatility, so even the most cutting-edge printers and processes for the novel materials have not gone beyond the seven categories specified by ASTM (American Society for Testing and Materials) and ISO (International Organisation for Standardisation) standards. To match the growth of unique materials and newer requirements for products, 3DP is now a vital component of a multi-process system as well as an integrated way of numerous systems. Nevertheless, it must never be viewed as a standalone method [26]. 3DP is a relatively newer, quickly developing manufacturing technique that has reported numerous uses in the automobile, health-care, defense, aerospace, and many other fields. Applications in the medical fields that have been found to be revolutionizing surgical techniques, upending the prosthesis and implant markets, along with dentistry, will be discussed in this chapter. We will also touch briefly on the more recent areas of bioprinting, which include cell printing [27].

15.1.5 Role of 3D printing in aerospace and automobiles sectors

3DP technologies sharpened the industries like aircraft in current years. 3DP technology develops the production of the complex as well as small structures much more conveniently. 3DP processes apply a consecutive layer-by-layer addition of the materials to produce/develop objects from a geometrical computer design. Progressively, any form of design may be customized and developed using the 3DP technique. The fabrication of components can be done at a minimal cost using 3DP technology based on user-defined criteria. In contrast to previous plastic-forming techniques, tooling costs associated with the creation of molds were disregarded. It is feasible to produce highly customized structures in smaller quantities. Therefore, the aircraft industry has a greater need for this technology. This chapter attempts to give an overview of 3DP technology and how they are used in the aerospace industry. This chapter covered elements, materials, or components along with their attributes that were primarily developed for use in the aircraft industry [28]. One of the emerging manufacturing technologies is 3DP, also called additive manufacturing. By utilizing more advanced processing methods of 3DP, it is becoming clearer in numerous domains how powerful and promising it is. Worldwide 3DP is common. 3DP has shown its effectiveness in manufacturing 3D models, mostly in the automotive, aerospace, and medical industries. By creating or scanning the specific components with the aid of designing software, the existing as well as nonexistent components in various domains may be manufactured. With the aid of a 3D printer, we can print them. With the use of additive manufacturing, we can create lighter or more durable products faster. The com-

ponents had also been made with the aid of various metal and plastic materials. In the automotive and aerospace industries, rapid prototyping is found to be one of the time-saving techniques for 3DP. 3DP is currently being developed to address human health issues by producing human organs using a specific human's tissues. It is a time- as well as a money-saving strategy. When compared to other conventional manufacturing techniques, additive manufacturing is found to be more environmentally friendly for both people and the environment. The products made via additive manufacturing also offer good levels of safety. Additionally, raw material waste can be avoided [29].

15.1.6 Role of 3D printing in food industries



Fig. 15.4: The role of 3D printing in food industries.

Figure 15.4 represents the application of 3DP in the food industries. A significant force driving the continuing paradigm shift in the development methodologies of many industrial fields has arisen as 3DP technologies. The use of specific natural as well as synthetic biomaterials (like hydrogels) as the bioinks and the incorporation of 3DP into tissue engineering are paving the way for the development of several novel solutions for significant healthcare and biomedical challenges. This also heralds newer frontiers in the pharmaceutical, food, and medical industries [30].

15.1.7 Role of 3D printing in medical

3DP is a technique which is used to create the three-dimensional shape of any object in a digital mode. Once it was very difficult to implant the 3DP in medical field, but nowadays by the help of technologies and advancement this technique is used in

pharmaceutical industry at broad level to create the 3D structures of drugs in a specific manner and enable a higher production of the medical implants as well as changing the route that the surgeons as well as doctors plans the procedures [31]. This method, which has a broad impact on the medical industry, involves five steps to reach the desired outcome: choosing the anatomical target area, developing the 3D geometry through the help of the processing of an images obtained from MRIs or CT scans, optimizing for physical printing, as well as choosing the right 3D printer and materials. The file prepared by using these steps are further used in slicing then the sliced image is going for 3DP [32–35].

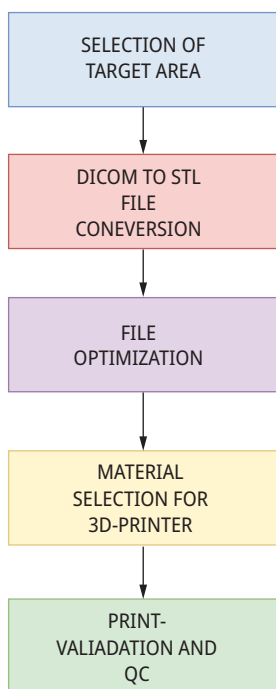


Fig. 15.5: The 3D printing workflow.

Figure 15.5 represents the dimensional printing workflow. This technique improves the level of research and knowledge, increases the level of disease understanding, also defines the patient-specific designing of the implantable devices as well as the surgical tools and optimizes the surgical cost and process. This analysis involves the usage, limitation and importance of 3DP in the medical field. 3DP is nowadays applicable in various medical fields, like cardiology, surgery, neurosurgery, gastroenterology, maxillofacial and oral surgeries, otolaryngology, ophthalmology, plastic surgeries, orthopedic surgeries, podiatry, pulmonology, transplant surgeries, radiation oncology, urology, as well as vascular surgery [36–45]. Along with that this technique is broadly used in personalized treatment, preparing customized surgical tools, improvement of medical education, Stor-

age of the rare cases for educational purposes, improving forensic practice, Bioprinting, Customizing synthetic organs and many more. Many researches have shown that patient-specific presurgical planning may decrease the reduced operating room time as well as result in fewer complications. This is just one of the therapeutic benefits of using 3DP in personalized treatment. The technique gives the surgeon a 3D model of the anatomy of the patient that can be applied to precisely plan the surgical approach in conjunction with the cross-sectional imaging, or it can be applied to manufacture unique prosthetics (or the surgical tools) based on the anatomy of the patient [46–49]. With the help of 3DP, it is possible to select with extreme precision the size of the prosthetic components prior to implantation. 3DP also provides the customized surgical tools and prostheses, which reduce the manufacturing cost as well. It will also improve the forensic practice, used to demonstrate various anatomical abnormalities. The technique is also used to model the implantable tissue, for instance, 3DP of the synthetic skin for transplanting to patients especially in case of burn injuries. Hence it may also be applicable for the testing of different chemical, cosmetic, as well as pharmaceutical products. 3DP is also used in preparing customized organs; bioprinted organs are now in use to replace the animal model for toxicity analysis in the pharmaceutical industry. Along with all these usage and applications 3DP technology also impacts various dreaded diseases like cancer, congenital heart diseases, endovascular diseases, intestinal disease and many more. Cancer is one of the most dreaded diseases on the globe, but it has a lot of loops in its management, especially in the area of surgery and drug development. Technologies like 3DP give us a great foundation from which to improve cancer management. It assists in the presurgical planning, serves as a teaching aid for patients as well as trainees, and also to facilitate cancer surgery [50, 51]. The applicability of 3DP has benefited surgeons in surgical planning, decreased the danger of the procedure's duration, increased its therapeutic efficacy, and raised awareness of the application of the 3DP in the treatment

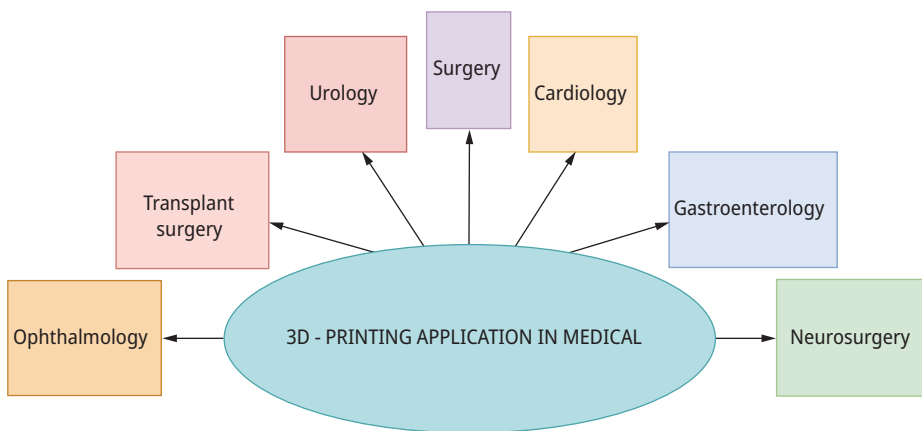


Fig. 15.6: Three-dimensional printing application in medical.

of different cancers [52]. Three-dimensional bioprinting is also used in cardiac tissue engineering [53]. 3DP is utilized to show the geometric links between intra and extracardiac components in congenital heart disease and aids in the creation of digital heart models as well [54–63].

Figure 15.6 represents the 3DP applications in the field of medicine such as urology, gastrology, neurosurgery, transplant surgery, ophthalmology as well as cardiology.

15.1.8 Role of 3D printing in agriculture

The quickest prototyping method which may combine the material science, computation, as well as control technologies is 3DP. The applications of 3DP to the food started mainly with the digitally controlled extrusion operations which may develop the deposition of the materials layer by layer from the pre-designed files like that of computer-aided design (CAD) or the SLA. A lot of research emerged with the strong efforts in using the 3DP technology to several designing of the food products. As in the initial stage, the materials applicable in food 3DP were found to be limited to chocolate products, but currently, a lot of materials are successfully applied as well as their characteristics in the 3DP were also reported (such as pea protein, potato starch with an wheat, pea protein, gels made up of lemon juice, corn starch, alginate with the cereal food, the oat protein, surimi, and the meat product. Applications for 3DP had been followed by more trial-and-error attempts as well as conservative designs, which might have led to a waste of resources as well as experimentation time. This is partially because of the unawareness of appropriate tools for predicting the process' results. The performance of 3DP is currently predicted and quantified using computational approaches, namely the computational fluid dynamic (CFD) simulation, according to patents relating to the technology [12]. Soils are found to be a key environmental compartment offering a lot of products that derive basically from their agricultural applications, as well as other services beneficial to human well-being. A lot of soil properties, like minerals, their composition in the soil organic matter, plant as well as microorganisms, their physical structure, and also their spatial arrangement, determine the health of soil. Healthy soils are responsible for delivering tangible economic as well as environmental benefits to the human communities, farmers and businesses. They carry the capacity to respond to the agricultural intervention as well as also be helpful for the generations of both the optimal biomass productivity as well as the provision of the other ecosystem services [16]. 3DP is currently used widely in several applications. So from the manual labor to the formation of the machines which support us in manufacturing of products which we consume as well as the things which carry practical applications, the additive manufacturing offers the creativity of these as we channel our several ideas from the digital to that of tangible. By the help of this recent technology, we are able to utilize our time as well as capital that would be allocated with that of the conventional process of manufacturing that often goes through convoluted as well as lengthy processes. It

benefited us to adhere to sustainability along with also efficient manufacturing as it constantly proves efficient applications in several fields as well as industries [22].

15.1.9 Role of 3D printing technology in fashion designing

3DP method's major goal is to make the many difficult notions a reality. Majorly, 3DP technology is evolving continually with the designers' interest as well as the professionals in the fields of technologies. It offers novel avenues of the fascinating as well as never ending possibilities for the fashion designers. As in this method the object is performed layer by layer without the involvement of any types of mold, depending upon its designing that were done by the help of CAD as well as applicability of powder particles materials, such as metals, resins, as well as plastics. 3DP technology may also offer several perspectives in almost each and every region of life. This type of innovation was impacting a novel industrial revolution along with creating vibes, in mainly all the industries. Regarding 3DP, there were a lot of technologies and ways were developed by many professionals, but this type of outrageous technologies is carrying an obstacle in the field of fashion apparels, such as materials, that were basically synthetics as well as are lacking the natural properties for the production of the desired silhouettes [64].

15.1.10 Role of 3D printing in building and construction industry



Fig. 15.7: Constructability benefits of 3D printing technology.

Figure 15.7 represents the benefits of the 3DP technology in the field of construction such as better productivity, geometric freedom, faster construction, short supply chain as well as low cost.



Fig. 15.8: Sustainability benefits of building and construction industry by 3D printing.

Figure 15.8 represents the sustainability benefits of the building and construction industries by the help of 3DP technology. It was discovered that 3DP, also called additive manufacturing, is a cutting-edge manufacturing process that automatically creates complex shapes and geometries from a 3D CAD model without the need for additional fixtures, tooling, or dies. Today, this type of automated manufacturing method is applicable to several emerging sectors of industries due to the significant benefits of producing functional prototypes in a reasonable building time with less human intervention and material wastage.

Therefore, there is a growing applicability of this technology to the built environment, enhancing our conventional building strategies while reducing the requirements for additional formwork, higher capital investments, and human resources. Research interest in employing 3DP for construction and building has exponentially increased in the past few years [65].

15.1.11 Role of 3D printing in pharmaceuticals

Figure 15.9 represents the pharmaceutical applications of the 3DP technology.

Recently, we came to the brink of the Fourth Industrial Revolution. Due to the remarkable technological advancements of the twenty-first century, the term “manufacturing” is currently being digitized. In the past decade, there has been a rapid increase in the field of prototyping, which offers individual patient care and can serve as a training and educational tool, as well as contribute to research.

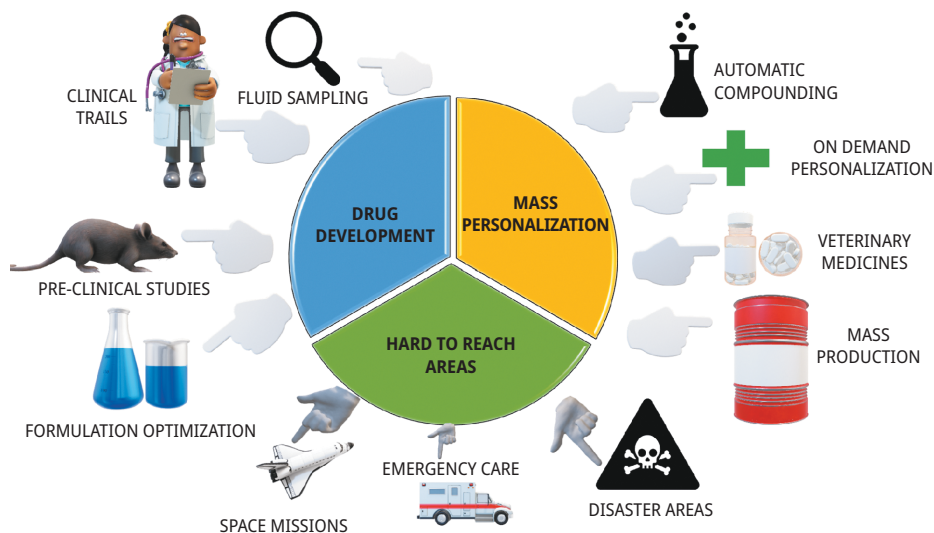


Fig. 15.9: Pharmaceutical applications of 3D printing technology.

Innovative technologies like 3DP have the potential to cause a paradigm shift in medicine manufacturing, design, and application. Instead of using conventional large batch methods, customized printlets (3D printed tablets) with tailored shapes, doses, sizes, and release characteristics must be developed on-demand. Therefore, the pharmaceutical industry has never before experienced transformative technology in the manufacturing of medicines.

Hence, this technology must be utilized at every stage of the drug development process, from preclinical research and development to the first-in-human clinical trials, and finally to front-line medical care, also known as personalized medicines [66].

15.1.12 Role of 3D printing in engineering

The model of reverse engineering 3DP at the time of writing is not available. For respiratory support there are many efforts that are continuously ongoing by the engineer which are mainly focusing on developing the adoption of existing products. 3DP is presently used for making ventilator splitter in such a way which is adapted like a single ventilator with multiple patients to get different levels of oxygen requirement. At that time many 3DP laboratories can parallelize the process of 3DP with multiple printers and the resource should be assigned judiciously. In my recommendation the 3DP expert communicates with their local hospital supply chain. The 3DP community must work equally. At the time of COVID-19 crisis, the safety of 3DP lab has to be followed continuously. The 3DP community plays a vital role in the rapid and efficient

process which influences or attracts the company and regulatory bodies to work with 3DP. 3DP can have important roles in patient education, diagnosis, treatment, and so on with the hope of improvement in medicine. Also the 3DP will impact a position mark at the time with new open source models, description of intended use target printed description [67]. The major role of 3DP in the medical application is to help in diverse fields like pharmaceuticals. Medical companies create more specific drugs that also help in the rapid productivity of the medical implants and changing in the way that the doctors as well as the surgeons plan the process. 3DP is an additive technology which is expected by many industries in the manufacture as it involves 3D solid objects which are virtually represented in the digital form. 3DP technology in the areas of medicine has multiple applications itself. To improve the research knowledge the relation and dependency between the patient and surgeon the 3DP has much potential. 3DP has been widely applicable in the sectors of healthcare which involves neurosurgeon cardi surgery, gastroenterology podiatry, pulmonology, urology, orthopedic surgery, plastic surgery & vascular surgery. It also personalizes the patient's needed quantity. 3DP drugs consist of printing out the layers of the powdered drug to form it to dissolve faster than that of the average pills. 3DP also offers to protect the life of patients to reduce the waiting list of patients who need transplant in the field of synthetic organs. To make the dose of medicine more effective to the patient the 3DP offers us to design the drug in a particular shape and size as the shape of the capsule differs it doesn't lead to different doses as well as the drug properties [68]. The major properties of 3DP in the areas of medical application are a state of the art. 3DP approaches for cardiac tissue. As a result of greater surface tension as well as one-sided cell adhesion in cell culture flasks and dishes, 3DP-based cell culture techniques have been shown to be superior to 2D conventional cell culture techniques. Furthermore, cell movement alignment and physiology were demonstrated by CM cultured within 3D scaffolds. Using a 3D tissue engineering approach, we change the calcium dynamic, electric impulse, and also the temperature. Cardiac tissue constructs functionalized 3D scaffolds with incremented proliferation, physiology as well as viability of cell movements. This function to construct 3D scaffold-based tissue engineering acts as an alternative for in vivo drug screening as existing animal models of drug screening do not match exactly with the human physiology. Animal immune systems are simpler than human immune systems to use disease models for the screening of drugs. When drug development is screened through 2-dimensional cell culture assay and animal disease models screen results are false positive or false negative. More than 20% of drugs, such as antihistamines, benfluorex, prokinetic agents, pergolide, and antipsychotics or antibiotics, are taken off the market due to cardiac cytotoxicity. 3DP techniques provide alternative development of heterogeneous 3D scaffolds with a strong mechanical strength carrying all of the needed characteristics and an ideal scaffold for the cardiac tissue engineering. In the second scaffold-free category of bioink or direct printing substrate, individual cells made of bioink are used as tissue spheroids. The lack of organ donors for transplantation has been addressed by 3DP based on tissue engineering and

stem cell technologies, which have the potential to deliver patient-specific tissue replacement. 3D groove patterns are made of hybrid as well as heterogeneous material to resemble the morphology of the natural extracellular matrix (ECM). Cell movement, morphology, phenotype, and physiology are the main features of 3D pattern groove and influence. 3DP technology prints the ECM-based scaffolds with a higher resolution. Latest 3D scaffold based on printing technique bioinks that are composed of cell and desired biomaterial directly prints a scaffold in the form of the organ for the production of full as well as partial organ [69].

3DP is termed to be a transformative approach to an industrial productivity which can enable the formation of stronger, lighter parts as well as systems. The 3DP is a form of the term additive manufacturing which may offer the fabrications of the items directly from the digital files, offering the user for virtually producing any solid object on demand. Additive manufacturing or 3DP is an engineering method of developing 3D products by adding layer upon layer of material in the precise geometric shape. A variety of materials can be used in additive manufacturing, such as plastic, metals, concrete, or human tissue. 3DP is of various types, for example: solid-based 3DP, liquid-based 3DP. This method or process is a fast-developing manufacturing technology. The incrementing demand for 3DP is due to its benefits such as rapid prototype as well as production of customizable parts. These are termed to be major factors for its growth in the last three decades. Hence, the method or technique has currently become one of mainstream manufacturing methods [70].

3DP or, we can say, the additive manufacturing applies the CAD software for designing the model which is to be printed [71]. 3DP has revolutionized the engineering industry by empowering engineers to create complex structures, parts and machines easily and prototypes quickly and is profitable as well. 3DP uses light and cost-effective materials with effective and worthy life [72, 73]. 3DP has become prominent in engineering, as it provides a number of advantages over that of traditional manufacturing processes [74]. Some of the roles of 3DP in engineering sectors are:

- **Prototyping:** Engineers can apply 3DP to quickly produce prototypes of parts, allowing them to test as well as refine their design before committing it to expensive tooling or production run.
- **Customization:** 3DP enables engineers to build or to produce highly customized and complex parts and structures which would be much difficult or, we can say, impossible to create with the traditional manufacturing process. The 3DP allows engineers to create customized parts, that is, parts that are built according to choices and requirements for the needful. This is particularly useful in industries such as aerospace and medical, where each component needs to be tailored to a specific application.
- **Production:** Additive manufacturing or 3DP can also be useful for small-scale production of specialized components. This is particularly useful in aeronautical engineering and the automobile industry, where a small number of high-performance components are needed.

- **Tooling:** 3DP can be used to form molds, jigs as well as fixtures, decrementing the cost and time that were associated with the traditional tooling methods.
- **Reduced cost:** 3DP can reduce the cost of manufacturing by eliminating need of expensive tools and reduced waste.
- **Improved design:** 3DP allows engineers to produce complicated beautiful small-to large-scale structures.
- **Faster production:** 3DP enables engineers to produce parts and components more quickly than traditional manufacturing methods, which can help reduce lead times and improve overall efficiency.
- **Small batch production:** 3DP allows engineers to produce small batches of parts economically, making it a cost-effective solution for low-volume manufacturing.
- **Material development:** 3DP can be used to detect material property. Engineers can use 3DP to experiment with new materials and to create new compositions of materials [75, 76].

Engineering is a widely spread field all over the world. 3DP of most medical instruments or any medical-related things is all based on engineering. Let us talk about tissue engineering. Tissue engineering techniques or strategies are often referred to as the artificial growth of organs in laboratories. Biomaterials are used in tissue engineering techniques. Biomaterials are materials that provide 3D space for artificially implanted tissue to attach, grow, and form novel tissues with an appropriate structure and function. Tissue engineering is an integrative approach that combines life sciences, computer modeling, and materials engineering to produce functional and artificial tissue constructs for biomedical applications. In this technique, an arena with an ECM nature is applied to repair and regenerate processes.

Tissue engineering basically use three types of the materials for cardiovascular tissue engineering, hence they are mentioned below:

1. **Natural:** Alginate, hyaluronic acid, collagen, fibrin, chitosan, and gelatin.
2. **Synthetic:** polycaprolactone, PLA, polyglycolic acid, poly-D, L-lactic-co-glycolic acid
3. **Hybrid:** The combination of the synthetic, natural as well as the metallic materials.

These materials are applicable to formulate 3D scaffolds to imitate the primitive ECM as well as present the same morphology to cells as they may exit from an original organ. So, an ideal arena for cardiovascular tissue engineering must be biodegradable, biocompatible, as well as carry enough electrical and mechanical strength conduction to do the dynamic functions of our heart [77]. Bone tissue engineering is also a great example and shows the role of 3DP in engineering precisely. Engineered bone tissue was observed as a potential alternative to that of conventional applicabilities of the bone grafts, because of their limitless supplies as well as zero disease transmission. The term “bone tissue engineering” targets to induce newer functional bone regeneration via the interdependent combination of the biomaterials, the cells, as well as the factory therapy. Bone tissue engineering is an integrated approach which can

utilize cells as well as biomaterials to reinstall needed functions of the tissues. The scaffolds are beneficial parts of the bone tissue engineering. Bone tissue engineering by the help of 3DP provides an adequate solution for the diagnostics of orthopedic patients. It offers an arena according to the shape and size and applies a similar method which is done by a body to regenerate tissue. Many researches are being done on 3DP in the sector of bone tissue engineering and a total number of 257 articles have been identified till September 2019. The first article was posted in 2004, then in 2005, and three articles were uploaded in 2006. From 2007 to 2011, many articles had been identified [78].

15.2 Conclusion and future prospects

Additionally, this chapter explores the latest advancements in 3DP of personalized drug-eluting implants, medical devices, and printlets. It covers 3D printed tablets with individualized characteristics such as size, shape, dose, and release properties. Furthermore, the chapter provides an overview of the current state of 3DP in the medical field, encompassing topics such as surgery, dentistry, and the bioprinting of organs tailored to individual patients. It also discusses the potential impact of recent developments like 4D printing on the future of drug delivery and patient treatment pathways.

The pharmaceutical product development industry is constantly evolving and designing novel delivery systems to enhance the therapeutic effectiveness of pharmaceuticals. Leveraging 3DP technology, customized and individualized medications have been developed to offer improved therapeutic benefits for numerous patients. The application of 3DP in the preparation of biomedical devices and drug delivery systems has brought about a paradigm shift in the healthcare sector.

Additionally, this chapter addresses the production of 3D printable batteries and supercapacitors by connecting the current performance requirements with specifications for printable energy-storage materials, casings, electrolytes, and electrodes. It outlines the needs for the upcoming generation in this field.

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Gulshan Goyal*, Ajay Kumar and Arjun Gupta

16 Recent developments in 3D printing: a critical analysis and deep dive into innovative real-world applications

Abstract: 3D printing has seen a significant surge in the past few years, leading to a wide spectrum of innovative real-world applications in various fields, including biomedical, construction, industrial and space exploration. 3D printing has enabled the production of lightweight and intricate parts for space exploration resulting in cost savings and increased efficiency. It has also enabled the creation of customized prosthetic limbs and soft robotic structures that replicate the behavior of an actual heart. Apart from this, it can revolutionize the way emergency homes and low-cost housing are built. This chapter provides a comprehensive review of the latest advancements in the field of 3D printing and its novel uses in different fields. The chapter delves into the application of 3D printing in biomedical, construction and space exploration applications. The existing research, deployed projects, as well as case studies are reviewed. The analysis done in this chapter shows that 3D printing has remarkable potential to revolutionize various industries, and future research in this field can lead to more innovative applications in the near future.

Keywords: 3d printing, construction, industrial, disaster, housing, biomedical, space exploration, logistics, customization

16.1 Introduction

The process of 3D printing starts with CAD (computer-aided design) design and ends with a finished product. With a view to providing an understanding of technology and its potential, the whole 3D printing process is viewed from concept to finished product. The entire step-by-step process is described in Fig. 16.1.

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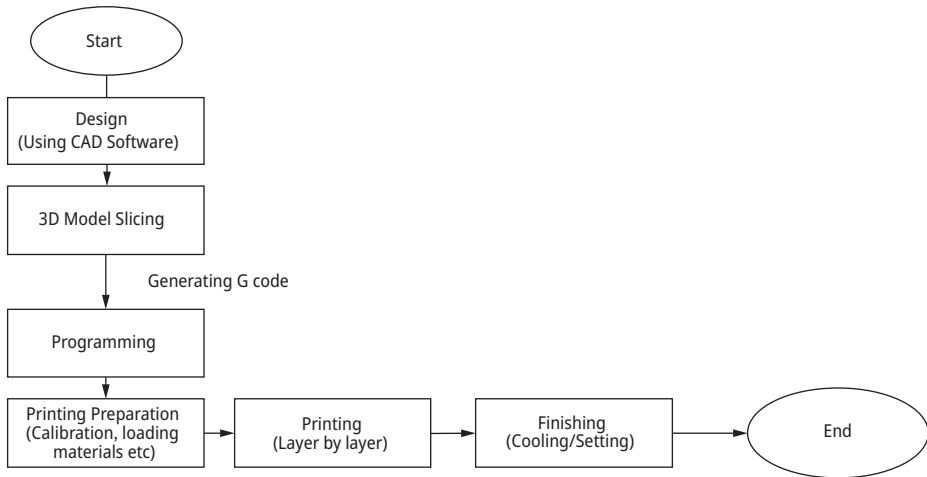


Fig. 16.1: The process of 3D printing.

Various steps are explained below:

a) **CAD modeling**

CAD modeling is the starting point of 3D printing. A 3D model of the object intended for printing is created using CAD software. Creating an object layer by layer is the way a 3D model can be created. After finishing, the model is saved in a format that can be read by the 3D printer [1].

b) **Slicing**

The next step is slicing. Slicing can be described as the process of breaking a 3D model into multiple layers. The slicing software then generates instructions for the 3D printer on how to create each layer. The instructions include the thickness of each layer, the speed of the print head, and the temperature of the material.

c) **Printing**

Once the model is sliced, the printing process begins. The 3D printer begins to create the object layer by layer, which it will read from the instructions provided in the slicing software. The printer uses a variety of materials, such as plastic, metal, or even wood, to build the object. The material is melted, extruded, or sintered depending on the type of printer used.

d) **Finishing**

After the object is printed, post-processing is required to finish the product. This can include removing support structures, sanding or polishing the object, or painting it. Support structures are used during the printing process to hold up overhanging parts of the object, and they must be removed once the printing is complete. Sanding or polishing may be required to smooth out any rough edges or imperfections. Finally, painting can be used to add color and texture to the object [1].

e) **Quality control:**

Quality control is an extremely important step in the process of 3D printing. The finished product must meet certain specifications, such as accuracy, strength, and durability. To ensure that the product meets these specifications, quality control checks are performed throughout the printing process. This includes checking for the accuracy of the 3D model, monitoring the temperature and speed of the printer, and testing the final product for strength and durability.

16.2 Nature of work

The primary goal of this chapter is to review recent developments and applications of 3D printing. The study uses a combination of systematic and comprehensive review and comparative analysis to examine the potential of 3D printing technology in these fields, including its challenges and opportunities. The chapter starts by providing a background of the evolution of 3D printing since its inception. It provides an introduction to 3D printing and its basic principles. The chapter then discusses its applications in various fields such as biomedical, space and construction.

It involves a comprehensive search of multiple data sources to identify relevant studies, which are analyzed and compared to traditional manufacturing methods using data from different case and experimental studies. The further organization of the chapter is as follows. Section 16.3 contains the background history of 3D printing, Section 16.4 provides detail of the methodology used, in Section 16.5 the literature on applications of 3D printing is reviewed, and Section 16.6 discusses the opportunities and gaps identified. Overall, the proposed research aims to provide a critical analysis of recent developments and innovative applications of 3D printing, highlighting its potential to revolutionize various fields and addressing the challenges and opportunities associated with its use.

16.3 Background

The process of 3D printing involves additive manufacturing, where layers of ink, commonly referred to as filament, are added to create an object. Various materials like thermoplastics, metals, and glasses are used for this ink, with thermoplastics being the most prevalent. Over the years, significant milestones and breakthroughs have shaped the development of 3D printing, resulting in a wide range of technologies and applications available today [2].

The original concept of 3D printing was initially conceived in the 1970s, but practical experiments did not take place until the early 1980s. Dr. Hideo Kodama, a Japanese researcher, is attributed to the first rapid prototyping technique. In 1981, he

introduced a manufacturing method based on a layer-by-layer approach, similar to stereolithography (SLA), where a photosensitive resin is solidified under ultraviolet light.

Around the same time, a group of French engineers also explored SLA. Regrettably, they abandoned the project due to a lack of business prospects.

Nevertheless, the interest in 3D printing persisted. In 1986, C. Hull filed the initial patent for SLA. By 1988, the company introduced its first commercial product, the SLA-1, which marked the birth of 3D printing. The significant events of the 1980s are summarized in Tab. 16.1.

Tab. 16.1: Key events related to 3D printing in the 1980s.

Year	Key events
1980	Dr. Kodama patents rapid prototyping in Japan
1984	French engineers develop stereolithography, later abandoned
1986	Charles Hull adopts stereolithography
1988	The first SLA-1 machine introduced

The 1990s witnessed significant advancements in the progression of additive manufacturing. As the fundamentals were firmly established, prominent manufacturers of 3D printers emerged, new technologies were refined, and the development of 3D modeling tools commenced, propelling additive manufacturing to new heights.

In 1992, Stratasys was granted the FDM (fused deposition modeling) patent and developed numerous 3D printers catering. From 1993 to 1999, various companies surfaced within the sector of 3D printing, each employing unique technologies and techniques.

Simultaneously, the availability and enhancement of CAD tools continued to expand, facilitating the creation of 3D models. Sanders Prototype, commonly known as Solidscape, was among the first companies to develop specialized tools used for additive manufacturing.

In recognition of his contributions to the advancement of 3D printing, in 2014, Hull was honored with the European Inventor Award by the European Patent Office [2].

The key events of the 1990s are summarized in Tab. 16.2.

Tab. 16.2: Key events related to 3D printing in the 1990s.

Year	Key events
1990	First EOS Stereos system was created by EOS GmbH
1992	Stratasys was granted the FDM patent
1993	Solidscape is founded
1995	An exclusive license from MIT obtained by Z Corp
1999	Innovations in medicine brought by engineered organs

The 2000s saw significant advancements in 3D printing technology, making it more accessible and affordable. Rapid prototyping technology, which had previously been expensive and limited to large corporations, became more accessible to small businesses and individuals.

In 2003, Stratasys released the Dimension 3D printer, the first 3D printer for under \$30,000, which made FDM technology available to a wider audience. Meanwhile, the patent on Selective Laser Sintering expired in 2006, making it possible for other companies to develop and sell SLS machines. The key events of the 2000s are summarized in Tab. 16.3.

Tab. 16.3: Key events related to 3D printing in the 2000s.

Year	Key events
2000	SLM technology introduced by MCP Technologies
2005	Z Corp. unveils HD color 3D Printer, Spectrum Z510
2006	Reprap (an open-source project) begins
2008	Development of the first 3D printed prosthetic leg
2009	Creation of Sculpteo

The 2010s saw a rapid expansion of 3D printing applications across various industries, from aerospace to healthcare. The technology made it possible to create custom-made prosthetics, dental implants, and surgical tools, among other things.

With the increased demand for 3D printing services, the industry diversified into different segments, such as 3D printing software, materials, and services. Companies like Materialise, Shapeways, and Sculpteo emerged to provide 3D printing services to businesses and individuals.

In recent years, 3D printing has continued to evolve, with new technologies like metal 3D printing and multi-material 3D printing emerging. Today, 3D printing is used in everything from architecture to fashion, and the possibilities for its use seem endless.

In this chapter, the applications of new advancements in this rapidly evolving field of 3D printing are reviewed.

16.4 Methodology

The authors use a combination of systematic review and comparative analysis as the methodology. The systematic review allows us to gather and analyze existing literature on recent developments and innovative applications of 3D printing technology. This methodology involves a comprehensive search of multiple data sources to iden-

tify relevant studies. We present the findings to provide an analysis of recent developments and innovative applications of 3D printing technology.

In addition, we use comparative analysis to examine the pros and cons of 3D printing technology in comparison to traditional methods. It involves a detailed examination of the costs, time, quality, and environmental impact of 3D printing and traditional manufacturing methods using data from different case and experimental studies.

16.5 Applications

The technology has advanced rapidly in recent years, and its applications have grown from its early uses to create small plastic models and prototypes and now has innovative applications emerging in several sectors [3, 4]. These applications are shown in Fig. 16.2.

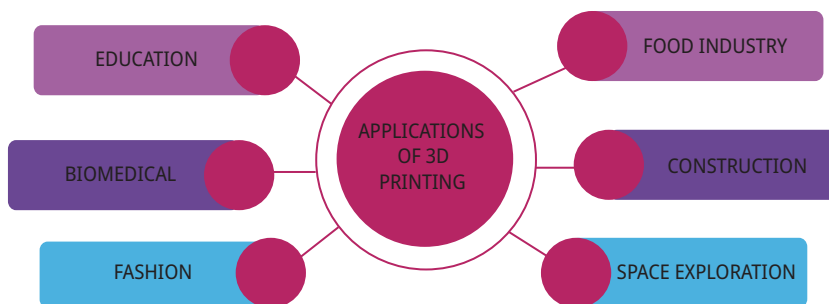


Fig. 16.2: Applications of 3D printing.

The chapter deals with the application of 3D printing in biomedical, construction, and space exploration applications. These applications are discussed in detail in subsequent sections.

16.5.1 Applications in the biomedical industry

The biomedical industry has been one of the earliest adopters of 3D printing technology, utilizing it to create customized prosthetics, implants, and even entire organs. The ability to print organs has the potential to revolutionize transplantation medicine, as it reduces the risk of rejection and eliminates the need for donors. Additionally, 3D printing technology can also be used to create personalized medical devices that are tailored to a patient's unique anatomy, thus improving their outcomes and quality of life. This technology can also be used to create models of organs for surgical planning and training, reducing the risk of complications during surgeries [5, 6].

16.5.1.1 3D printed organs

The field of medical 3D printing has made significant strides in recent years, particularly in organ transplantation. The shortage of organs for transplantation has been a major challenge in healthcare for years, and 3D printing offers a solution by enabling the creation of artificial organs that can be tailored to a patient's specific needs [7, 8].

The potential of 3D printing to create human organs has been widely studied in recent years. It offers a solution to the shortage of organs for transplantation and reduces the rejection risk. It also allows for testing and experimentation before implantation, improving patient outcomes [9].

Moreover, the use of 3D printing in medicine could also lead to cost savings in the long run. By creating customized organs and models, doctors can reduce the risk of complications and improve patient outcomes, ultimately reducing the need for repeat surgeries and hospital stays [10, 11].

Recently, engineers from MIT have developed an innovative procedure that utilizes 3D printing technology to produce an accurate replica of a patient's heart without the need for invasive methods. This replica effectively imitates the patient's blood-pumping capacity, enabling doctors to customize treatments based on the unique structure and function of the individual's heart. Additionally, the team has also achieved printing of a patient's aorta using the same methodology. To replicate the heart's pumping action, the researchers have created sleeves that encase the printed heart and aorta. In the future, this procedure could potentially allow doctors to print a patient's heart and aorta, subsequently implanting various valves in a printed model to determine the optimal design that ensures the best functionality for the specific patient [12].

The researchers also hope that their approach could eventually lead to more personalized treatments for patients with heart disease, and they are currently working on scaling up the process to produce heart replicas for more patients [13].

16.5.1.2 Prosthetics

Amputees often encounter difficulties with prosthetic arms and wrists, primarily due to their weight and size, leading to discomfort and coordination issues. These challenges arise when the prosthetics do not fit in a proper manner. To tackle this problem, 3D printing has emerged as a solution, enabling the creation of lighter prostheses to suit each individual amputee [14, 15].

Nevertheless, the cost and accessibility of prosthetics remain significant obstacles, particularly in underdeveloped nations. Recent efforts have focused on developing an affordable and functional prosthetic hand capable of performing basic tasks for individuals who have undergone hand and/or forearm amputations. This prosthetic hand is constructed using 3D printing technology and controlled by a brain-computer interface

which receives the electroencephalography (EEG) signals as an input. This prosthetic hand is constructed using 3D printing technology and controlled by a brain–computer interface which receives the EEG signals as an input. These signals drive the actuators which are connected to cables, enabling the actuation of the 3D printed wrist and fingers [16, 17].

Specifically designed for individuals with trans-radial upper-limb extremities resulting from injuries or congenital conditions, the 3D printed prosthesis is highly sensitive and can utilize biopotential signals to activate the upper extremities' digital movements, thereby facilitating load-carrying capacity [18].

Overall, 3D printed prosthetics offer adaptability to different users and are recommended for hospital use where cosmetic and corrective surgeries are done. This technology has the potential to significantly enhance the lives of amputees, particularly those residing in underdeveloped regions, by providing affordable and functional prosthetic solutions [19, 20].

16.5.2 Applications in construction

At a fraction of the time and costs of conventional construction methods, 3D printing technology is applied in the building industry to construct durable buildings that can be maintained for decades. The 3D printing technology may be used to produce whole buildings, bridges, as well as all infrastructures. In addition, it is possible to design and create custom building components through 3D printing which will reduce waste and increase efficiency [21, 22].

16.5.2.1 3D printed buildings

The construction industry is currently grappling with labor shortages, as evidenced by reports such as those by the Associated Builders and Contractors and the National Bureau of Statistics of China. Additionally, declining productivity and occupational health risks have necessitated a transformation and upgrade of the industry. Enter 3D printing technology, which has revolutionized the design and manufacturing processes in construction. By replacing traditional casting and solidifying processes with layered extrusion, 3D concrete printing technology eliminates the need for formwork, simplifies manual steps, and reduces manpower. It also improves safety by taking over some risky operations. However, challenges still exist when applying 3D concrete printing to real-scale building constructions due to material properties and printer mechanisms, leading to additional processes that consume time, materials, and manpower [23, 24].

16.5.2.2 Emergency response structures

Over the past 20 years, as reported by the United Nations, natural disasters have affected a staggering 4.4 billion individuals, resulting in 1.3 million fatalities and economic losses totaling 2 trillion dollars. The impact of such disasters on the environment is diverse, with some changes immediately observable. However, the health consequences for affected populations are highly unpredictable, influenced by various factors that contribute to the spread of diseases and other health-related issues in the aftermath of such events. Fortunately, many of these factors can be mitigated through careful planning. The long-term consequences of disasters include damage to healthcare facilities, diagnostic equipment, as well as critical infrastructure such as roads and bridges. Outbreaks of diseases following disasters are frequently associated with population displacement. Additionally, access to healthcare services, particularly reproductive health needs, may decrease during these times. To address these challenges, the utilization of technology, such as 3D printing, has proven effective in developing sustainable and resilient infrastructure and planning. This cost-effective and innovative approach allows for the production of parts and the disruption of supply chains. Its portability, affordability, and ability to produce plastic objects on-demand in remote areas make it particularly attractive in disaster-prone regions. Organizations like Field Ready, Oxfam, and the American Red Cross have successfully employed 3D printing in disaster-stricken areas such as Haiti and Nepal, envisioning a transformative shift in meeting needs during disasters, in developing countries, and in low-resource regions. Some benefits of this are given below [25, 26]:

On-site manufacturing: This has become an attractive means of producing vital parts in remote locations. In some disaster-stricken areas, plastic pipes that supply clean water to victims have been joined incorrectly due to a lack of proper equipment. This situation can lead to sepsis and other health hazards. Although some local NGOs have resorted to makeshift methods, such as compression fittings, these solutions are not always readily available. Transporting a 3D printer to the site to model a fitting and print it solves several problems. For example, a 3D printer can be used to produce clean umbilical cord clamps on-site, which are inexpensive and hygienic [26].

On-demand manufacturing: With a little training, it is possible to design critical components and parts based on need. The materials that are used to print such parts may be stored instead of keeping a record of them. Production of different parts can be made using the same material, eliminating the need for intermediary work, and reducing waste. Case studies provide examples of successful on-demand manufacturing solutions that meet a variety of needs [27].

On-time manufacturing: Collaborating with local manufacturing technologies enables the production of vital parts precisely where and when they are needed. 3D printing allows for efficient manufacturing, easy setup, and cost-effectiveness, mitigating the impact of supply chain disruptions during disasters. This approach emphasizes openness to learning, experimentation, and collaboration with diverse stakeholders. Field Ready,

Oxfam, and the American Red Cross have successfully implemented this strategy in disaster readiness and relief efforts in Haiti and Nepal. Their vision is to revolutionize how needs are addressed in disasters, developing countries, and low-resource areas [28].

Given below are some case studies on the usage of 3D printing in disaster response:

a) **Umbilical cord clamp**

In Haiti, neonatal umbilical sepsis contributes to 5% of newborn deaths. However, the procurement of essential umbilical cord clamps, which prevent sepsis, solely relies on costly bulk imports from China. Reliance on volunteers to bring clamps in their luggage makes the supply chain vulnerable to disruptions. As an alternative, local substitutes like shoelaces are utilized, increasing the risk of sepsis and improper cord closure. On-site production of customized and hygienic umbilical cord clamps presents a cost-effective solution, allowing for large-scale manufacturing to meet local preferences [29].

b) **Ventilator connector**

A hospital in Nepal had a requirement for single-ended connections to the ventilator but they had just one that is available at all, so it had to be bought with other parts of the ventilator kit. The hospital's engineers cut a single-ended connector into two pieces and glued them together. Measurement and model of the original part were sufficient to make a dual-ended design, which was produced by 3D printing [29].

c) **Connector for electrocardiogram (ECG) limb leads**

ECG cuffs are placed on the wrists and ankles of patients in order to monitor electrical signals from the heart. The hospital was, however, plagued by problems with the disconnection of clamps during use due to a lack of an appropriate connector. Although the connector had been originally attached by glue or tape, it turned out that this makeshift fixing was no longer permanent. A 3D printer was used to produce a new connector with much tighter tolerances in order to solve the problem [29].

d) **3D printed modular homes**

Businesses have been producing 3D printed houses which look like LEGO bricks in China. The modular homes are fireproof and designed to withstand a magnitude 9 earthquake. The buildings are constructed with a specific construction material from industrial and agricultural waste that contains no carcinogenic substances like formaldehyde, ammonia, or radon.

The above case studies show the revolutionary and crucial role 3D printing has played in disaster-stricken areas around the globe and highlight the future possibilities of using 3D printing for disaster response.

16.5.3 Applications in space exploration

The applications of 3D printing technology in space exploration are numerous and highly promising. 3D printing allows astronauts and engineers to quickly create parts and tools on demand, reducing the need for costly and time-consuming supply missions from the Earth. This technology has the potential to revolutionize the way we design, build, and maintain spacecraft in space [30, 31].

One of the important benefits of 3D printing in space travel is the ability to manufacture parts and tools that are customized to specific mission requirements. This can include everything from replacement parts for spacecraft to specialized tools for scientific experiments. By manufacturing parts and tools on demand, astronauts can quickly repair and replace critical components, reducing the risk of mission failure due to equipment malfunctions [32].

Another key application of 3D printing in space travel is the potential to manufacture habitats and infrastructure on other planets. By using locally available materials, 3D printers could be used to build habitats and infrastructure in situ. This could significantly reduce the cost and complexity of future space missions, while also enabling longer duration human exploration of other planets.

There are serious obstacles to space exploration, with a particular focus on Mars for extended missions. Overcoming the weight-to-cost ratios during launch and travel is crucial for optimizing human presence in extraterrestrial environments. At this time, the journey to Mars will take about six to nine months, which could be problematic in particular with regard to a critical first phase of colonization. Nevertheless, the introduction of additive manufacturing or 3D printing capabilities at sites could be a potential solution. This technology reduces the number of days, months, and even hours needed to deal with demand from day to hour or minute by enabling flexibility in just-in-time logistics.

The logistics business is a complicated area, even on the Earth where variables like expectations of consumer needs, production times, cost versus quantity, shipment and storage are necessary for successful support to end users. Small-scale logistics will be as essential to the continued exploration of our planet as launching systems or travel time effects on humans, whether it's NASA or a private company like SpaceX. In terms of science, there are a few problems with 3D printing on Earth scenarios, but the cost/benefit of small-scale production is not widely explored [32].

Given in Fig. 16.3 is data from the Planetary Society which shows the cost of Project Apollo and Project Gemini, both actual and Inflation Adjusted. It is clear from this table that the cost of space travel has only increased in the past and 3D printing shows great promise in reducing this cost [33].

As far as logistics and prices are concerned, the flexibility of 3D printing is apparent since all parts are custom produced for ordering on demand. The \$90 million cost to transport 800 kg of printers and materials by using additive production systems that allow them to send raw material at a flat rate keeps the price fixed. Beyond tech-

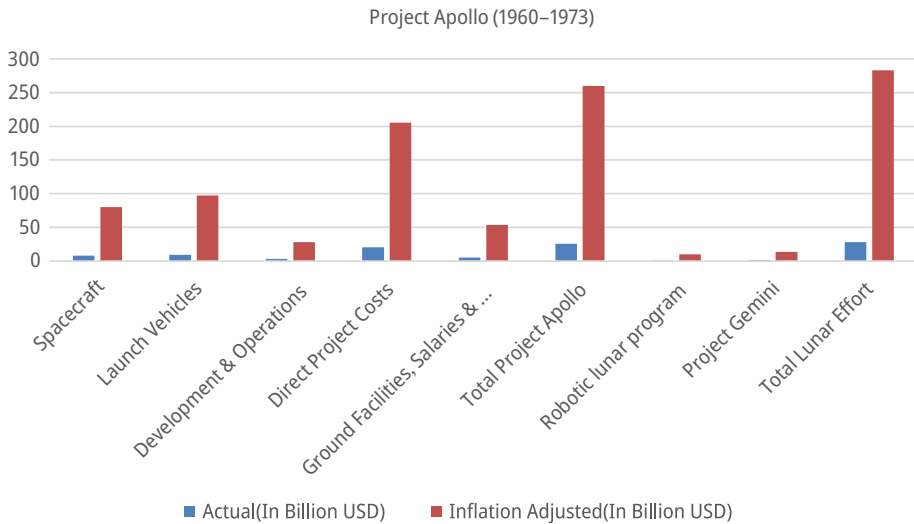


Fig. 16.3: *Apollo* mission cost comparison.

nology development, consideration of practical use and impact on costs must be more widespread to move forward. For interplanetary travel, 3D printing might be able to provide flexible, timely logistics [34].

16.6 Discussion

This chapter has evaluated and reviewed new developments in 3D printing and their applications in the fields of biomedical industry, space exploration, and construction. Based on this review and comparison, given below are the opportunities and current gaps in the application of 3D printing in these sectors.

16.6.1 3D printing in biomedical industry

16.6.1.1 Opportunities

1. **Personalized treatment:** 3D printing has shown significant promise in printing human organs such as hearts and aortas that can mimic the patient's blood-pumping ability, providing doctors with a tool to tailor treatments to the patient's specific heart form and function. This personalized approach could lead to more effective and efficient treatments for patients with heart disease.

2. **Customized prosthetics:** 3D printing technology can create prostheses that are lighter and can be easily customized to fit the individual amputee, providing an affordable and functional option for individuals with upper-limb extremities resulting from injury or congenital conditions.
3. **Improved quality of life:** 3D printing in the biomedical industry can significantly improve the lives of amputees, especially those in underdeveloped countries, by providing affordable and functional prosthetics.

16.6.1.2 Current gaps

1. **Limited availability:** 3D printing in the biomedical industry is still limited and not widely available, especially in underdeveloped countries, which could limit its potential impact.
2. **Cost:** The cost of technology and material in 3D printing can be higher, which could limit its accessibility to patients who need it the most.
3. **Lack of regulatory approval:** In the biomedical sector, where 3D printing has not yet been regulated, it could lead to a reduction in the use and global acceptance of this technology.
4. **Lack of awareness:** There is a lack of awareness about the potential benefits of 3D printing in healthcare among patients and healthcare providers, which could limit its adoption and use.

16.6.2 3D printing in construction

16.6.2.1 Opportunities

1. **Flexibility and customization:** 3D printing allows for greater design flexibility and customization, especially for small-scale or one-off projects.
2. **Reduced lead times:** 3D printing allows for rapid prototyping and on-demand manufacturing, reducing lead times and enabling faster product development and delivery.
3. **Waste reduction:** Traditional construction methods can result in significant waste. 3D printing produces only the sections where needed, reducing material waste, and lowering environmental impact as well.
4. **Reduction in cost:** 3D printing can be more cost-effective due to a reduction in waste and construction time.
5. **Accessibility:** 3D printing can be done on-site and on-demand, making it a more accessible option for remote or disaster-prone areas where traditional construction techniques may not be feasible.

16.6.2.2 Current gaps

1. **Limited material selection:** As compared to traditional methods of construction, there is a very limited number of materials available for 3D printing.
2. **Quality control:** Ensuring consistent quality and accuracy in 3D printed parts can be challenging, especially for complex or large-scale projects. This requires careful monitoring and control of the printing process.
3. **Size limitations:** 3D printing is currently limited in the size of parts to be produced, which may make it unsuitable for large-scale construction projects.
4. **Skills and training:** The successful implementation of 3D printing in construction requires skilled personnel who are proficient in both digital design and the operation of 3D printers. Adequate training and educational programs are necessary to develop a skilled workforce that can harness the full potential of 3D printing technology in construction.
5. **Regulatory approval:** 3D printing is a relatively new technology, and regulatory frameworks for ensuring safety and quality standards are still being developed. This can create uncertainty and additional costs for companies seeking to use 3D printing for construction projects.

16.6.3 3D printing in space exploration

16.6.3.1 Opportunities

1. **Customization:** 3D printing technology allows for the customization of parts and tools according to specific mission requirements. This enables astronauts to quickly create replacement parts and specialized tools, reducing the need for costly and time-consuming supply missions from the Earth.
2. **Habitat and infrastructure manufacturing:** The ability to use locally available materials to manufacture habitats and infrastructure on other planets using 3D printing technology could significantly reduce the cost and complexity of future space missions while enabling longer duration human exploration of other planets.
3. **Timely logistics:** The potential for 3D printing to provide flexible, timely logistics for space exploration is significant. In establishing colonies on other planets, astronauts will be able to cope with unexpected challenges by shortening the time needed to identify a physical solution.

16.6.3.2 Current gaps

1. **Cost-effectiveness:** While 3D printing provides customization and flexibility, the costs involved in small-scale production are not widely examined. The costs of raw materials, printers, and other equipment needed for 3D printing may not be feasible for all missions.
2. **Material limitations:** While 3D printing technology can use locally available materials, such as regolith on the moon or Mars, the quality and properties of these materials may not be suitable for all applications. Therefore, there is a need for further research to identify and develop suitable materials for 3D printing in space.
3. **Technology limitations:** 3D printing technology has limitations, such as size and speed limitations, which may impact its effectiveness in space. Additionally, the technology may be affected by extreme temperatures and radiation exposure in space, which could reduce the lifespan of 3D printed parts and tools.

16.7 Conclusion

This chapter demonstrates the significant potential of 3D printing technology in various fields, including biomedical industry, construction, and space exploration. Specifically, the ability to print customized prosthetics, dental implants, and even human organs shows great promise in improving patient outcomes and revolutionizing the industry.

The development of a 3D printing procedure to create flexible and soft replicas of a patient's heart and aorta provides doctors with a tool to tailor treatments to a patient's specific heart form and function. This technology could potentially be used to implant valves into printed models to determine the best fit for a particular patient.

3D printing has been applied by the building industry to construct durable buildings that can be maintained for decades. In addition, the ability to rapidly deploy emergency response structures or portable hospitals in response to natural disasters or other emergencies using 3D printing can significantly reduce the time and cost of setting up such structures.

The potential applications of 3D printing technology in space exploration are also significant, as it can significantly reduce the cost and complexity of space missions and housing on other planets, making space exploration more feasible.

Overall, it is observed that 3D printing has great potential in the revolutionization of various industries, and future research in this field can lead to more innovative applications in the near future.

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17 Exploring design strategies for enhanced 3D printing performance

Abstract: The manufacturing industry has been significantly impacted by 3D printing, commonly referred to as 3D printing, as it has facilitated the production of complex shapes and structures. As the progression of this technology persists, it becomes imperative to investigate design strategies that can augment its performance. This chapter examines the subject of design optimization in the context of 3D printing, with a specific emphasis on the investigation of design strategies and the application of optimization techniques to enhance material utilization. This study examines a range of design strategies that have the potential to enhance the efficiency and effectiveness of 3D printing. The study investigates advanced techniques and methodologies, such as topology optimization and incorporation of complex geometry and lattice structures. Additionally, the chapter offers case studies and examples to offer practical perspectives on the implementation of these design strategies in the context of 3D printing. These real-world examples demonstrate the impact and effectiveness of the explored techniques and methodologies. This chapter serves as valuable resource for professionals, researchers, and designers operating within the 3D printing domain.

Keywords: Additive Manufacturing, Design Optimization, Lattice Structure, Topology Optimization, Design Strategies

17.1 Introduction

The manufacturing method which is known as 3D printing has advanced significantly and emerged as a disruptive technology in the manufacturing sector [1, 2]. The beginnings of 3D printing may be traced back to the 1980s when the first methods for rapid prototyping through 3D printing were developed. In the beginning, 3D printing was mostly utilized for concept modeling and design verification [3]. However, its applications have expanded over time to span a broad range of operations. The development

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of numerous 3D printing processes was an important turning point in the history of 3D printing [4]. Methods such as stereolithography, selective laser sintering, fused deposition modeling (commonly known as FDM), and selective laser melting methods as shown in Fig. 17.1 enabled the progressive production of products manufactured from a range of materials [5]. As 3D printing processes have expanded, material flexibility has risen, enabling the creation of components produced from a wide range of materials such as plastic, polymer, metal, ceramic, and composite [6]. As 3D printing gained popularity, it became clear that technique could be utilized for purposes other than prototyping. The industrial sector has recognized the benefits of 3D printing, such as enhance designed flexibility, less material waste and the ability to generate Complex structure that were previously impractical or impossible to achieve with traditional manufacturing procedures This realization spurred a change in emphasis toward optimizing design processes with the goal of improving 3D printing performance. The design strategies (Tab. 17.1) used in 3D printing include but are not limited to, geometric optimization, lattice structures, topological optimization, and material selection. These methods aim to enhance AM-produced goods' mechanical performance, weight, and material utilization. Designers may construct sophisticated geometries that fully use the potential of AM by

Tab. 17.1: Design strategies for enhanced 3D printing performance.

Design strategy	Description	Benefits
Topology optimization	Using algorithms to optimize the internal structure of a design for improved strength to weight ratio	– Reduces material usage and weight – Enhances structural integrity – Increases overall performance
Lattice structure	Creating designs with a lattice-like internal structure	– Provides lightweight and porous structure – Enhances material distribution and heat dissipation – Increases strength and stiffness
Parameter optimization	Adjusting printing parameters (e.g., layer thickness, printing speed, and temperature) for optimal results	– Improves print quality and accuracy – Minimizes warping and residual stress – Enhances part strength
Complex structure	Utilizing 3D printing to create intricate and highly complex geometries	– Enables the production of previously unachievable designs – Enhances functionality and performance in specific application – Supports customization and personalized manufacturing
Multimaterial printing	Printing objects with multiple materials, such as combining rigid and flexible materials	– Enables the creation of complex and functional designs – Enhances part functionality and versatility – Expands material options

utilizing the design flexibility provided by the technology, resulting in increased functionality and performance of the finished product.

This study centers on studying design strategies that may enhance the efficiency of 3D printing techniques. Despite substantial advances in 3D printing, several aspects still need further investigation and advancement [7, 8]. The matter of design strategies for improved 3D printing performance is a gray area of study where further research is needed to go deeper into the methodology and techniques used to optimize AM designs. Understanding and optimizing design factors and techniques in AM-produced components may result in increased mechanical performance [9], weight reduction [10], and effective material utilization [11]. Furthermore, to fully harness the capability of 3D printing, it is imperative that researchers look into additional areas of research. An area of interest pertains to the integration of reverse engineering with 3D printing [12]. Through the process of digitally capturing and converting physical objects into digital models, manufacturers have the ability to replicate complex geometries with high degree of precision and accuracy by employing 3D printing techniques. Furthermore, the advancement of printing file formats that are specifically designed for 3D printing technologies [13] offers standardized and optimized representation of digital models, guaranteeing compatibility among various 3D printing systems. Preprocessing and post-processing techniques are essential in enhancing the 3D printing process by addressing various challenges, including surface finishing, support structure generation, and dimensional accuracy [14]. Considerable research has been undertaken to investigate the wide array of materials that can be manipulated through 3D printing method [15], thereby introducing novel choice and enhancement. *The Handbook of Sustainable Materials: Modelling, Characterization, and Optimization* [16] provides a comprehensive overview of sustainable materials and optimization techniques, aligning with the principles of sustainable practices. By integrating sustainable materials and implementing optimization strategies, such as the reduction of material waste and energy consumption, 3D printing processes can be enhanced in terms of ecological sustainability and operational efficiency. In addition, the increasing areas of implementation of 3D printing in the field of orthodontics [17] underscore the utilization of 3D printing in specialized sectors, enabling the creation of customized dental devices and orthodontic appliances.

The aim of this chapter is to thoroughly investigate and analyze the design techniques used to improve 3D printing performance. The purpose of this study is to look at advanced design approaches, such as exploring complex geometry, optimizing material consumption, and investigating new material combinations, in order to maximize the mechanical performance and utility of AM-produced components. The study aims to give significant insights and assistance to academics, designers, and practitioners working in 3D printing by assessing current state-of-the-art methods for design. The ultimate objective is to enhance knowledge and methods of design for enhancing 3D printing efficiency, allowing the realization of high-performance, customized, and efficient products in an array of industries and applications.

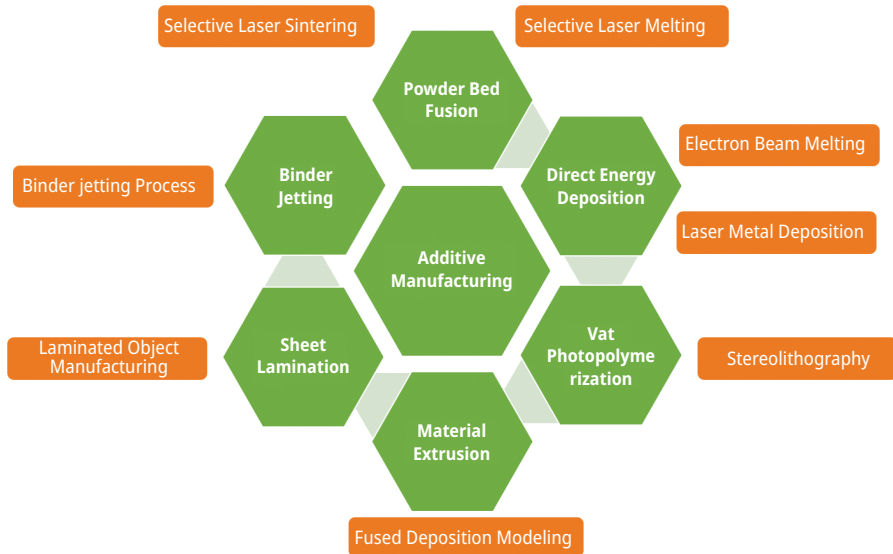


Fig. 17.1: Classification of 3D printing.

17.2 Design optimization in 3D printing

17.2.1 Exploration of design strategies

The optimization of design is a crucial component of AM that aims to investigate diverse design approaches with the objective of improving AM efficacy and attaining optimal outcomes. The distinctive features of AM, such as its capacity to fabricate intricate geometries and structures with exceptional accuracy, present novel prospects for design ingenuity and enhancement. Researchers in the field of 3D printing have been diligently working toward realizing the complete capabilities of design optimization to improve the performance of AM. The collaborative attempts of these individuals have resulted in noteworthy revelations and progressions across diverse sectors. Lin et al. [18] conducted a noteworthy investigation that demonstrated the utilization of design optimization and 3D printing techniques for the production of artificial corals as shown in the Fig. 17.2 intended for marine environments. Through the utilization of the flexibility provided by 3D printing, the scholars achieved the ability to intricately devise and produce coral formations that closely mirrored their authentic counterparts. The present study showcases the exceptional potential of 3D printing (AM) in attaining intricate shapes to improve both functionality and aesthetics.

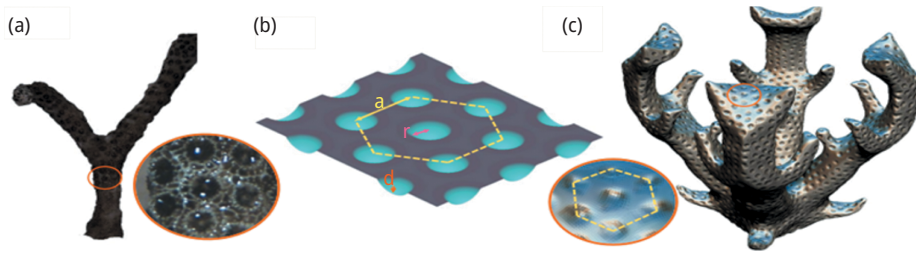


Fig. 17.2: (a) Physical structure and a close-up shot of *Seriatopora caliendrum*'s branch. (b) A pattern of depressions arranged in a matrix on a flat surface. (c) A physical model magnified view with dents.

Tang et al. [19] presented a framework aimed at minimizing the ecological footprint of products by means of design optimization for 3D printing. The approach adopted by them placed significant emphasis on optimizing material utilization, enhancing resource efficiency, and minimizing waste generation. By integrating these factors into the design procedure, scholars may attain more environmentally friendly results while leveraging the advantages of 3D printing technology.

The researchers delved deeper into the domain of cellular structures, where they discovered the noteworthy advancements made by Zhang et al. [21] in the realm of effective design optimization. The research conducted by the authors centered on hexagonal cellular structures with variable density. The study utilized 3D printing techniques to attain designs that are both high-performing and lightweight as shown in the Fig. 17.3. The study demonstrated the significant capabilities of 3D printing (AM) in producing structures with optimized geometries and properties, thereby opening up new avenues for improved performance.

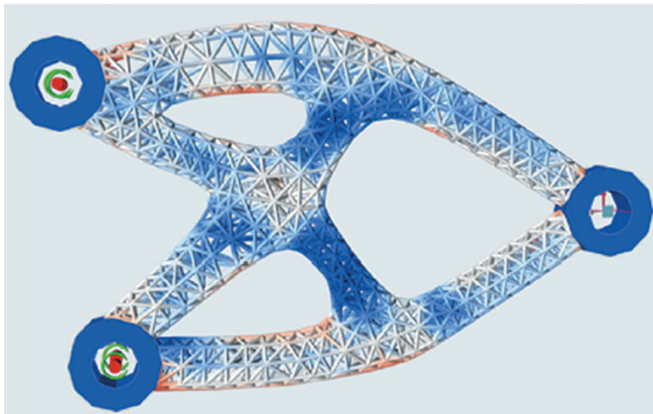


Fig. 17.3: Design optimization of a solid-lattice hybrid structure [20].

The optimization of thermal design has also been a central area of focus in the pursuit of progress in 3D printing. Pelanconi et al. [22] endeavored to optimize the radiative heat transfer in ceramic regular structures fabricated through 3D printing. The researchers endeavored to improve thermal performance in scenarios where effective heat transfer is of utmost importance by meticulously devising complex geometries. The present study emphasized the interdependence among design optimization, material selection, and 3D printing in attaining optimal thermal properties. Finally, the pursuit of improved performance prompted scholars to investigate the domain of heat exchangers. Bacellar et al. [23] develop and validate high-efficiency heat exchanger using approximation-assisted optimization and 3D printing technology. The researcher discovered the feasibility of integrating optimization approaches with editing manufacturing to create heat transfer devices that are both efficient and effective. This technique has the potential to create opportunities for enhancing energy management. In the area of 3D printing design optimization have identified efficient strategies for enhancing the performance of AM with the use of design flexibility and the introduction of material concern into the optimization technique. Tab. 17.2 shows various design strategies for additive manufacturing (AM) and design for additive manufacturing.

17.2.2 Optimization techniques for material usage

The utilization of design optimization techniques for material usage in 3D printing received a significant interest due to the difficulties associated with elevated production expenses and the requirement for post-fabrication treatments [24] as shown by the Fig. 17.4a, b. The transition of AM from a prototyping technology to a production technology has resulted in an increasing need to enhance material utilization for the purpose of achieving cost-effective and efficient manufacturing processes, as noted by Vaneker et al. [24] In response to these concerns, scholars have investigated the notion of design for 3D printing (DfAM), which endeavors to enhance product design by considering the intricacies of AM procedures and the advantages throughout the product's lifespan [24].

A challenge commonly encountered in 3D printing pertains to the utilization of a temporary support material throughout the production process to avert the occurrence of component collapse or warping [25]. Gaynor and Guest [25] have observed that the inclusion of support material leads to an increase in material consumption, build time, and post-processing demands. They proposed an approach to address the aforementioned concerns by incorporating a minimum allowable self-supporting angle into the topology optimization framework. The inclusion of this limitation enables the creation and production of components and structures without the requirement of auxiliary material, leading to noteworthy reductions in material consumption and post-production procedures [25]. Gaynor describes a method that utilizes a sequence of projection operations to satisfy the minimum length scale criterion and provide sufficient support for overhanging features. They claim that the manufacturing or design engineer provides

Tab. 17.2: Design strategies for additive manufacturing (AM) and design for additive manufacturing (DfAM).

Design strategy	Description	Specific DfAM method	Application
Topology optimization	Using algorithms to optimize the internal structure of a design for improved strength to weight ratio	Topology optimization for AM	Aerospace, automotive, medical implants
Lattice structure	Creating designs with a lattice-like internal structure	Lattice design for AM	Lightweight structure, biomedical implants, energy storage
Parameter optimization	Adjusting printing parameters (e.g., layer thickness, printing speed, and temperature) for optimal results	Parameter optimization for AM	High-precision components, tooling, customized products
Multimaterial printing	Printing objects with multiple materials, such as combining rigid and flexible materials	Multimaterial design for AM	Wearable devices, consumer products, robotics
Complex structure	Utilizing 3D printing to create intricate and highly complex geometries	Complex structure for AM	Art sculptures, microfluidics, advanced engineering

the self-supporting angle as an input variable, which is contingent on the particular 3D printing process. They have also shown that the algorithm's efficacy in addressing topology optimization problems is evidenced by its ability to meet the minimum length scale and overhang constraints. Notwithstanding its potential for success, the suggested methodology does possess certain constraints. Gaynor and Guest have noted that the sequential nature of the projection scheme is congruent with the 3D printing process. However, it may impede computational efficiency by constraining parallel processing. They have noted that the existence of numerous embedded nonlinear functions in the topological variables may result in convergence difficulties for intricate design problems. Gaynor suggests that the optimization technique's effectiveness can be improved by addressing the challenges through parameter tuning and algorithmic improvements. Their team suggest that the incorporation of optimization techniques in 3D printing can enable designers and engineers to surmount the constraints related to support material, thereby facilitating the realization of productive and economical manufacturing procedures. According to Gaynor and Guest, the suggested methodology provides a significant design instrument for assessing the cost-performance trade-offs associated with manufacturing limitations. Further investigation and enhancement of these optimization methodologies will facilitate the transformative impact of 3D printing on various sectors, as it will facilitate the fabrication of intricate, lightweight, and utilitarian parts with maximized material efficiency.

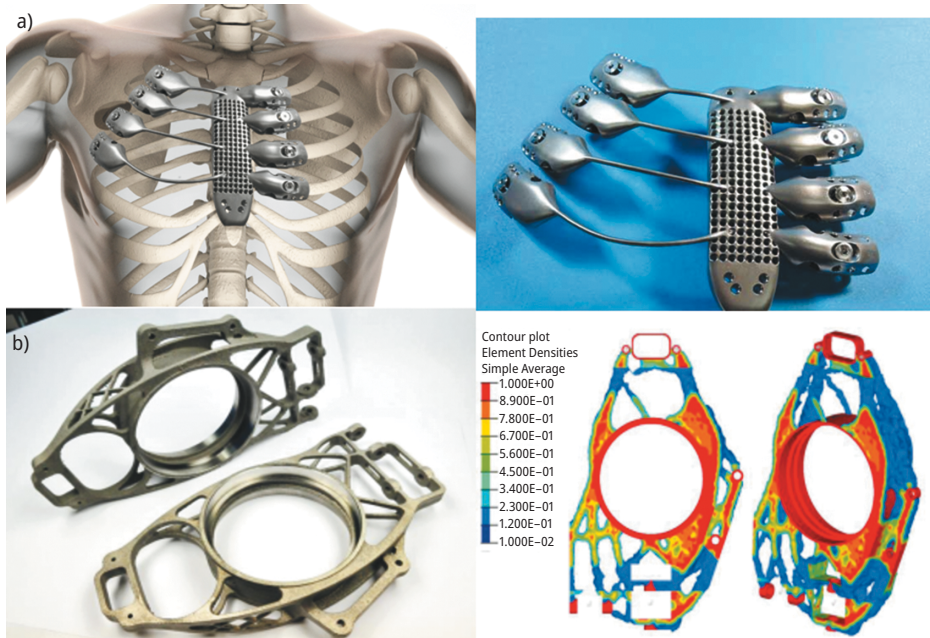


Fig. 17.4: (a) World's first 3D-printed ribs transplantation empower cancer patient's recovery [26]. (b) Topologically optimized upright of a car suspension, printed with electron beam melting of Ti-6Al-4 V ELI (with permission [27]).

17.3 State-of-the-art techniques and methodologies for AM design optimization

Significant progress has been made in three primary areas of 3D printing design optimization, namely topology optimization, complex geometries and lattice structures, and cellular design [28]. These methodologies attempt to investigate design approaches that augment the efficiency of 3D printing and streamline the design procedure for components produced through 3D printing. Topology optimization is a widely used methodology that aims to produce optimized designs by allocating material throughout a designated design domain, while simultaneously fulfilling predetermined performance specifications and manufacturing limitations. The approach employs mathematical optimization algorithms, including density-based techniques, evolutionary structural optimization (ESO), and the level set method (LSM), to progressively enhance the material distribution [20]. This results in complicated high-performance structures that are difficult to achieve using traditional design approaches. Complex geometry and lattice arrangements are also being optimized in 3D printing design. The word “complex geometry” refers to an intricate and organic form that provides various functional structure advantages. Advance

design approaches, such as generative design algorithms enable the automatic creation of optimized designs that conform to user specified constraints and objectives. To use these approaches a large for the Rapid analysis of numerous design possibilities, resulting in improved performance and effectiveness. Lattice structures have piqued the attention of researchers due to their amazing properties which include repeated cell like patterns, high strength to weight ratios and outstanding energy absorption capacities. The optimization of lattice structure topology and material distribution is crucial for enhancing mechanical properties like stiffness, strength, and fatigue resistance. sub structuring and multi material topology optimization approaches have been used to improve the optimization of lattice structures, resulting in increased effectiveness and practically in the manufacturing process. Cellular design, a sub field of latex structure, is focused on the creation of components with the internal cellular layout that gives superior mechanical characteristics and functionality. Cellular structures may be tailored to specific uses such as the fabrication of light weight and stiff aerospace components or the development of impact resistance structures that can absorb energy. Cellular structure optimization comprises adjusting cell size, shape, and connecting to achieve the required performance characteristics. The use of sophisticated methods and approaches in topology optimization, complex geometry and lattice structure cellular design contribute significantly to the investigation of design strategies targeted at enhancing 3D printing performance. Researchers may use these approaches to improve the design processing structural integrity, and optimize the functioning and effectiveness of adjectively built elements will stop for the research and development in these areas has the potential to reveal fresh design of opportunities and take 3D printing capabilities to new heights.

17.3.1 Topology optimization

The topology optimization technique has been developed as an advanced method for designing structures, aiming to generate diverse configurations that possess both light-weight characteristics and high-performance features. These configurations are challenging to achieve through conventional design approaches. 3D printing is an advanced manufacturing technique that constructs objects by incrementally layering materials together. This approach offers an alternative technique for fabricating intricate components. Jihong et al. [20] assert that the integration of topology optimization and 3D printing offers the potential to optimize the unique advantages and capabilities of both techniques, thereby presenting significant application prospects in contemporary manufacturing. Current scholarly investigations have been primarily dedicated to examining design methodologies aimed at enhancing the efficacy of 3D printing through the utilization of this particular amalgamation. In their study, Jihong et al. [20] conducted a comprehensive analysis of the current state of topology optimization within the domain of 3D printing. The significance of integrating material structure, process, and performance was underscored as a means to attain manufacturing that is light-

weight, multifunctional, and exhibits high performance. The article provides a comprehensive examination of various areas of study within the subject, including multiscale or hierarchical structural optimization design and topology optimization, with a specific focus on incorporating the limitations of 3D printing. In their study, Jihong et al. [20] draw attention to various concerns associated with the construction of lattice structures using additive manufacturing techniques. These concerns include the characterization of performance and the potential impacts on scale. Moreover, the present study investigates the anisotropy and fatigue characteristics of materials produced through additive manufacturing techniques. Additionally, it explores the challenges associated with functionally graded materials that are generated using 3D printing technology. The study conducted by Wu et al. [29] centered on the topology optimization of hierarchical lattice structures incorporating sub structuring. The current research examines the methodology of creating complex lattice patterns by dividing these structures into smaller components, with the aim of improving the optimization and efficiency of the manufacturing procedure. Kazemi et al. [30] have proposed a methodology to enhance the configuration of lattice structures consisting of multiple materials by employing geometry projection techniques. The researchers' methodology focuses on improving the allocation of materials within lattice structures to achieve desired mechanical properties and optimize overall functionality. The aforementioned studies highlight the ongoing research and advancements in topology optimization for 3D printing, particularly concerning complex geometries and lattice structures. The combination of topology optimization techniques and 3D printing has the potential to empower engineers in fully harnessing the capabilities of these technologies, thereby facilitating the creation of high-performance structures that demonstrate improved efficiency and functionality. The assumption in question is supported by the findings of recent studies conducted by Jihong et al. [20], Wu et al. [29], and Kazemi et al. [30].

17.3.2 Complex geometries and lattice structures

The study of complicated geometry and lattice arrangement is required for the research of design techniques aimed at increasing the performance of 3D printing, some of the ready to print lattice structure generate with the MATLAB are shown in Fig. 17.5. Gyroid, Voronoi, BCC, star, hexagonal, and diamond unit cells are shown in Fig. 17.5a–f, respectively. The word “complex geometry” refers to elaborate combinations and constructions that go beyond basic geometry forms. Complex geometry allows sophisticated design, which has the ability to optimize several elements of 3D printing, such as mechanical performance, weight reduction, and material utilization. Lattice structures, on the other hand, are a kind of complicated geometry that entails the organization of a repeating unit cell in a cyclic arrangement. The aforementioned structures are distinguished by unobstructed and interconnected arrangements of supports resulting in a light weight and structurally durable framework. Lattices may

be purposefully built with a very cell geometry, dimensions and alignments to achieve specific performance goals such as improve mechanical properties, optimized thermal conductivity, and increase energy dissipation. During the design process, the incorporation of complicated geometry and lattice structure may improve the effectiveness of 3D printing technology resulting in higher performance features. In contrast to traditional production processes, 3D printing has an inherent flexibility that allows for the simple realization of complicated geometry and lattice structures. This opened up new possibilities for optimizing design in a line with specific performance standards and constraints. The combination of complicated geometry and lattice structure may result in design with extraordinary properties such as increased strength to weight ratios, customized stiffness and flexibility, and improved functional integration. Implementing these design techniques not only makes it easier to create lightweight and efficient components but it also opens up opportunities for customization and innovation in variety of sectors including aerospace, automotive, biomedical, and architecture. It is notable that the utilization of complex geometry and lattice arrangements in 3D printing poses certain difficulties. The aforementioned factors encompass aspects pertaining to the soundness of the structure, choice of materials, limitations in production, and necessities for subsequent treatments. To tackle these obstacles, a multidisciplinary strategy is necessary, integrating knowledge in design optimization, materials science, computational modeling, and manufacturing procedures. To sum up, the investigation of design tactics aimed at improving the performance of 3D printing entails the incorporation of intricate geometries and lattice configurations. The aforementioned methodologies possess the capability to fundamentally transform the process of component design and production, resulting in enhanced efficiency, expanded capabilities, and heightened flexibility in design. Further investigation and advancement in this domain will facilitate the realization of the complete capabilities of 3D printing and its utilization in diverse sectors.

17.4 Case studies and examples

Various case studies offer valuable insights into the exploration of design strategies for enhanced strategies in 3D printing. Hale et al. [31] conducted a study that examines a digital workflow for the creation and production of customized orthoses through the utilization of 3D scanning as in Fig. 17.6a, 3D-printed part as shown in the Fig. 17.6b, and finally, the patient is wearing the orthosis in Fig. 17.6c. The research introduces an innovative methodology that effectively caters to the intricate medical requirements of an individual with a neurological ailment. The utilization of 3D scanning and printing technologies facilitated the implementation of algorithms for the purpose of generating 3D printable geometry and enhancing material distribution. By employing iterative prototyping techniques and incorporating feedback from the pa-

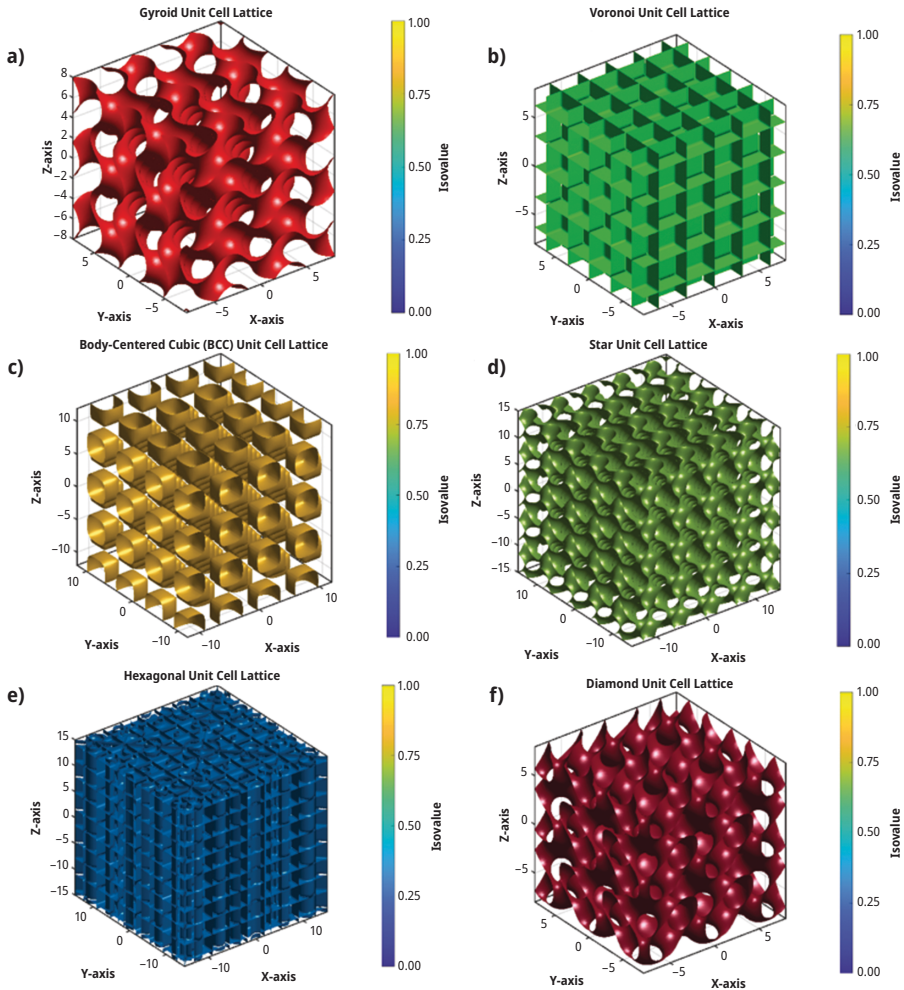


Fig. 17.5: Unit cell lattice structures generated using MATLAB: (a) gyroid unit cell lattice, (b) Voronoi unit cell lattice, (c) body-centered cubic unit cell, (d) star unit cell lattice, (e) hexagonal unit cell lattice, and (f) diamond unit cell lattice.

tient, a personalized orthotic device as shown in the Fig. 17.6. was developed to meet the specific needs of the individual. In this study underscores the prospective application of 3D printing in the expeditious production of customized orthoses, resulting in decreased lead times, enhanced patient adherence, mitigation of discomfort, and preemptive measures by decreasing the weight-by-strength ratio.

Wang et al. [32] present a noteworthy case study that showcases the efficacy of biomimetic design approaches shown in Fig. 17.7a and 3D printing techniques in the development of titanium alloy orthopedic implants Fig. 17.7b that exhibit improved

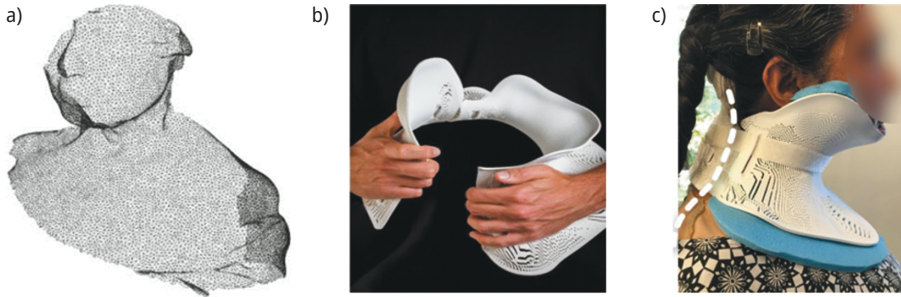


Fig. 17.6: (a) A 3D scan of the patient is acquired using 3D scanner. (b) The final customized cervical orthosis is produced by assembling the printed optimized design. (c) Finally, the patient is wearing the orthosis.

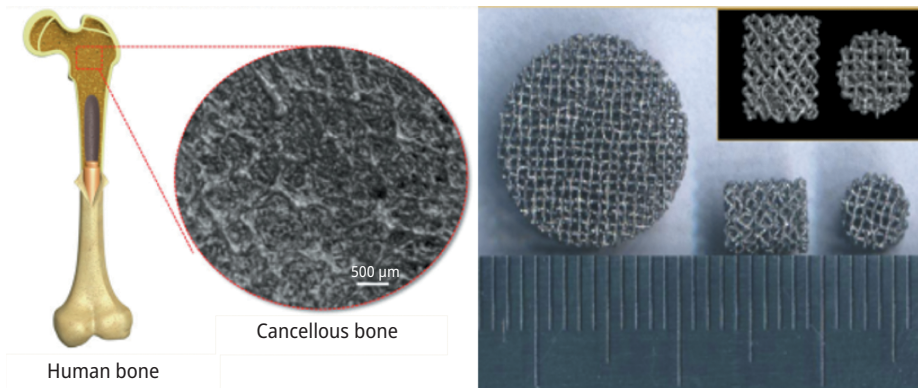


Fig. 17.7: (a) Human bone scaffolds and (b) artificial porous scaffolds with permission [32].

osseointegration. The present research demonstrates the utilization of 3D-printed porous scaffolds as shown in the Fig. 17.7 to tackle stress shielding concerns and attain optimal osseointegration capabilities.

Furthermore, the investigation conducted by Plessis et al. [33] delves into the examination of design elements inspired by nature, specifically by scrutinizing the body armor of *Glyptotherium arizonae*. The present study provides valuable insights into the potential design strategies that can be employed to improve the performance of 3D printing in protective materials. The study draws inspiration from the biomechanical optimization of osteoderms. The aforementioned collection of case studies serves as a valuable contribution to the investigation of design strategies aimed at improving the performance of 3D printing processes. These resources offer significant perspectives on enhancing the efficiency of safeguarding substances, customized orthotic apparatus, orthopedic implants, and the conceivable implementation of designs inspired by nature. The studies demonstrate the potential of 3D printing to transform multiple

industries and enhance performance and functionality through the use of advanced technologies, iterative prototyping, and analysis of natural structures.

17.5 Conclusion

This study has produced several significant findings by examining design strategies aimed at improving the performance of 3D printing. The implementation of intricate geometries and lattice structures has exhibited potential in optimizing mechanical characteristics and operational capabilities in components produced through 3D printing. The aforementioned design methodologies provide augmented strength-to-mass ratios, superior energy dissipation, and heightened thermal regulation capabilities. Topology optimization techniques have facilitated the development of structures that are both lightweight and high-performing through the systematic elimination of extraneous material. The aforementioned methodology has exhibited noteworthy capability in enhancing resource effectiveness and reducing expenses in 3D printing procedures. Finally, the optimization of material utilization through the consideration of factors such as support material and resource efficiency has demonstrated its criticality in attaining improved performance and sustainability within the realm of 3D printing. The implications of the research outcomes hold significant importance for the industry of 3D printing. Manufacturers can achieve superior performance characteristics of components by utilizing design strategies that integrate complex geometries, lattice structures, and topology optimization. The utilization of these constituents can result in enhanced product efficacy across diverse sectors such as aerospace, automotive, healthcare, and consumer goods, owing to their potential to be more robust, lightweight, and multifunctional. In addition, the optimization of material utilization plays a significant role in promoting sustainability initiatives by curbing material wastage and minimizing energy consumption in the production process. This study underscores the imperative of persistent innovation and exploration in 3D printing design strategies to augment performance. Subsequent investigations ought to prioritize the enhancement of comprehension and application of intricate geometries and lattice structures, exploration of innovative optimization algorithms for topology optimization, and formulation of effective methodologies for material utilization. Cooperation among researchers, designers, and practitioners is a crucial factor in advancing the limits of 3D printing design and realizing its complete capabilities. In addition, it is imperative to incorporate the principles of design for 3D printing (DfAM) into both engineering education and industry practices. This will facilitate the development of an innovative culture and encourage the widespread implementation of optimized 3D printing design strategies. The 3D printing industry has the potential to bring about a significant transformation in product development, manufacturing efficiency, and sustainability in the future, provided that it seizes the opportunities available.

17.6 Future directions and scope

The study of design strategies intended for improving the performance of 3D printing provides promising opportunities for future research and development endeavors. As the progression of technology persists, numerous crucial domains present captivating possibilities for research. An essential avenue for further study involves the incorporation of artificial intelligence and machine learning algorithms within the design optimization process. By utilizing these advanced computational techniques, it becomes feasible to automate and enhance the design process a more enhanced extent. This encompasses the advancement of intelligent algorithms capable of producing optimized design by considering desired performance criteria, material properties, and manufacturing limitations. Furthermore, the integration of multilateral printing capabilities offers a substantial opportunity for future investigation. The capability to fabricate objects utilizing diverse material possessing distinct properties presents novel opportunities for the development of intricate, utilitarian, and personalized commodities. Subsequent investigation might emphasize the advancement of design strategies that proficiently employ multimaterial printing techniques in order to optimize performance, functionality, and material efficiency. In addition, the incorporation of sustainable and ecologically conscious methodologies in the field of 3D printing holds significant implications for the future. Researchers have the opportunity to investigate design strategies and optimization techniques that place emphasis on the utilization of environmentally friendly materials, the reduction of waste generation, and the minimization of energy consumption throughout the manufacturing process. In conclusion, the prospects for 3D printing are contingent upon the ongoing investigation of design methodologies, incorporating of cutting-edge technologies, and implementation of environmentally conscious approaches. By considering these prospective avenues, 3D printing has the capability to fully realize its potential and bring about a paradigm shift in various industries through the facilitation of production of exceptionally efficient, functional, and personalized products.

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